# USE OF COAL DRYING TO REDUCE WATER CONSUMED IN PULVERIZED COAL POWER PLANTS

## QUARTERLY REPORT FOR THE PERIOD
## January 1, 2004 to March 31, 2004

by

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## ABSTRACT

This is the fifth Quarterly Report for this project. The background and technical justification for the project are described, including potential benefits of reducing fuel moisture, prior to firing in a pulverized coal boiler.

A theoretical model, for computing the effects of dryer design and operating conditions on performance of a continuous flow fluidized bed dryer, operating at steady state conditions, is described. Numerical results from the model, compared to data from a pilot scale lignite dryer located at Great River Energy's Coal Creek Station, show good agreement.

The dryer model was used to perform parametric calculations on the effects of dryer design and operating conditions on dryer performance and required in-bed heat transfer. Other analyses show the first order effects of firing lignite and PRB coals, dried to various moisture levels, on flow rates of coal, combustion air and flue gas, fan and mill power and unit heat rate.

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# INTRODUCTION

## Background

Low rank fuels such as subbituminous coals and lignites contain significant amounts of moisture compared to higher rank coals. Typically, the moisture content of subbituminous coals ranges from 15 to 30 percent, while that for lignites is between 25 and 40 percent, where both are expressed on a wet coal basis. Please see Appendix A for more details on definitions of coal moisture used in this report.

High fuel moisture has several adverse impacts on the operation of a pulverized coal generating unit. High fuel moisture results in fuel handling problems, and it affects heat rate, mass rate (tonnage) of emissions, and the consumption of water needed for evaporative cooling.

This project deals with lignite and subbituminous coal-fired pulverized coal power plants, which are cooled by evaporative cooling towers. In particular, the project involves use of power plant waste heat to partially dry the coal before it is fed to the pulverizers. Done in a proper way, coal drying will reduce cooling tower makeup water requirements and also provide heat rate and emissions benefits.

The technology addressed in this project makes use of the hot circulating cooling water leaving the condenser to heat the air used for drying the coal (Figure 1). The temperature of the circulating water leaving the condenser is usually about 49°C (120°F), and this can be used to produce an air stream at approximately 43°C (110°F). Figure 2 shows a variation of this approach, in which coal drying would be accomplished by both warm air, passing through the dryer, and a flow of hot circulating cooling water, passing through a heat exchanger located in the dryer.

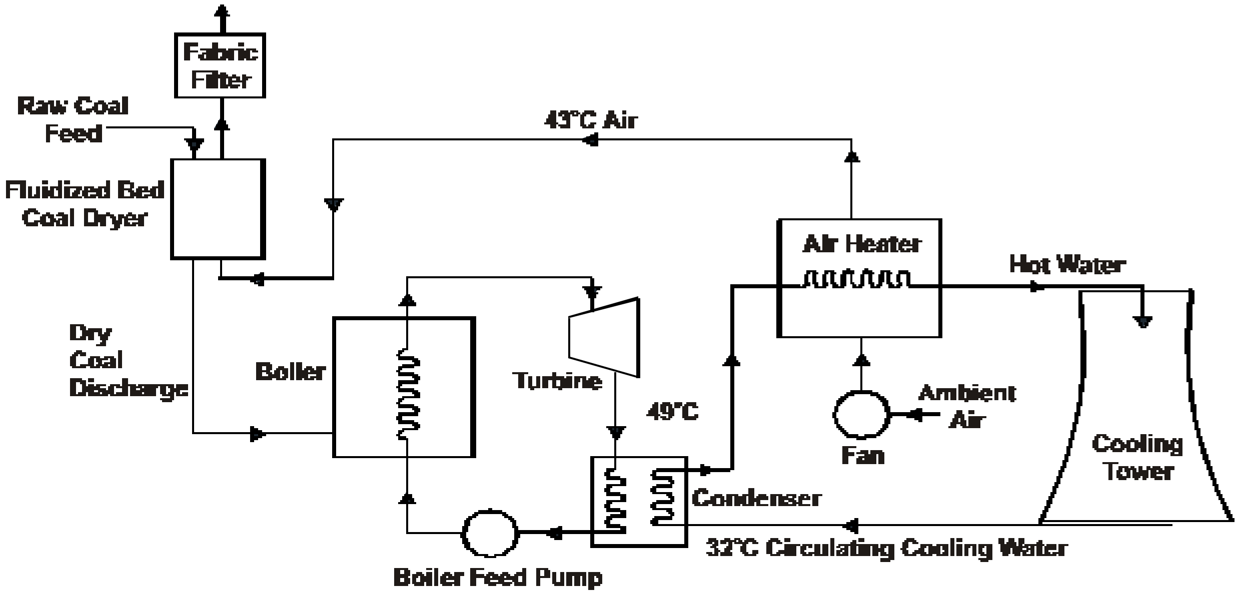


Figure 1: Schematic of Plant Layout, Showing Air Heater and Coal Dryer (Version 1)

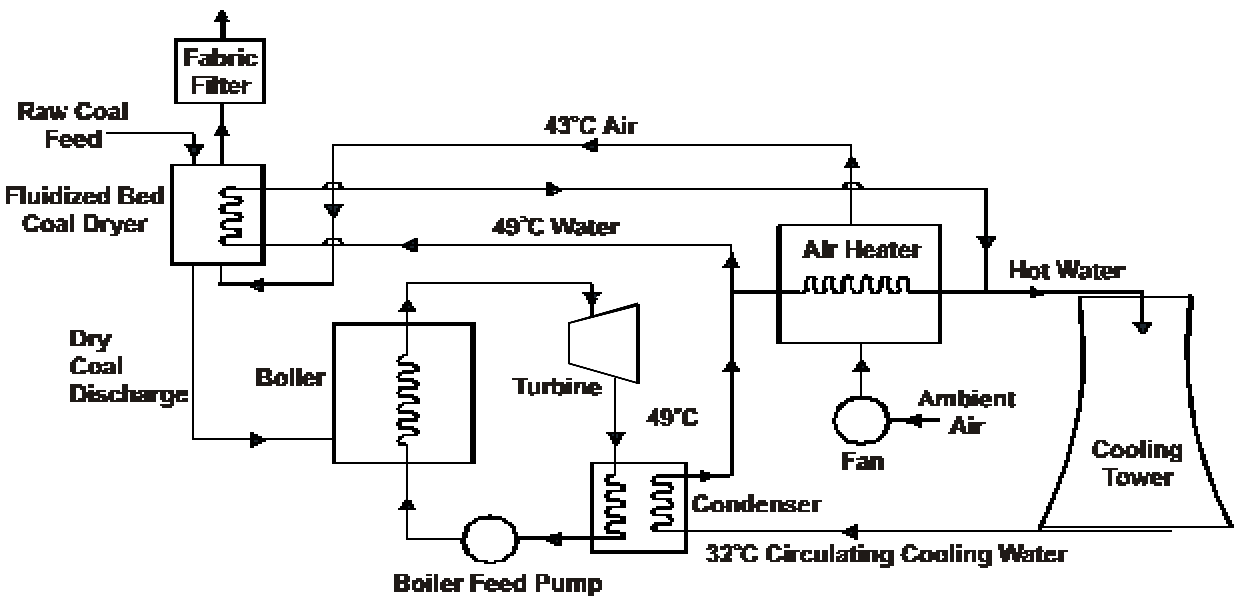


Figure 2: Schematic of Plant Layout, Showing Air Heater and Coal Dryer (Version 2)

## Previous Work

Two of the investigators (Levy and Sarunac) have been involved in work with the Great River Energy Corporation on a study of low temperature drying at the Coal Creek Generating Station in Underwood, North Dakota. Coal Creek has two units with total gross generation exceeding 1,100 MW. The units fire a lignite fuel containing approximately 40 percent moisture and 12 percent ash. Both units at Coal Creek are equipped with low $NO_x$ firing systems and have wet scrubbers and evaporative cooling towers.

The project team performed a theoretical analysis to estimate the impact on cooling water makeup flow of using hot circulating water to the cooling tower to heat the drying air and to estimate the magnitude of heat rate improvement that could be achieved at Coal Creek Station by removing a portion of the fuel moisture. The results show that drying the coal from 40 to 25 percent moisture will result in reductions in makeup water flow rate from 5 to 7 percent, depending on ambient conditions (Figure 3). For a 550 MW unit, the water savings are predicted to range from $1.17 \times 10^6$ liters/day ($0.3 \times 10^6$ gallons/day) to $4.28 \times 10^6$ liters/day ($1.1 \times 10^6$ gallons/day). The analysis also shows the heat rate and the $CO_2$ and $SO_2$ mass emissions will all be reduced by about 5 percent (Ref. 1).

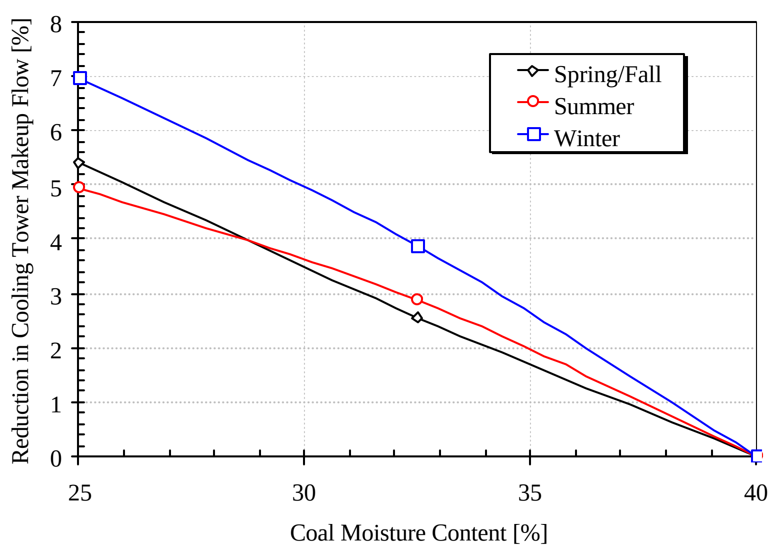


Figure 3: The Effects of Coal Moisture on Cooling Tower Makeup Water

A coal test burn was conducted at Coal Creek Unit 2 in October 2001 to determine the effect on unit operations. The lignite was dried for this test by an outdoor stockpile coal drying system. On average, the coal moisture was reduced by 6.1 percent, from 37.5 to 31.4 percent. Analysis of boiler efficiency and net unit heat rate showed that with coal drying, the improvement in boiler efficiency was approximately 2.6 percent, and the improvement in net unit heat rate was 2.7 to 2.8 percent. These results are in close agreement with theoretical predictions (Figure 4). The test data also showed the fuel flow rate was reduced by 10.8 percent and the flue gas flow rate was reduced by 4 percent. The combination of lower coal flow rate and better grindability combined to reduce mill power consumption by approximately 17 percent. Fan power was reduced by 3.8 percent due to lower air and flue gas flow rates. The average reduction in total auxiliary power was approximately 3.8 percent (Ref. 1).

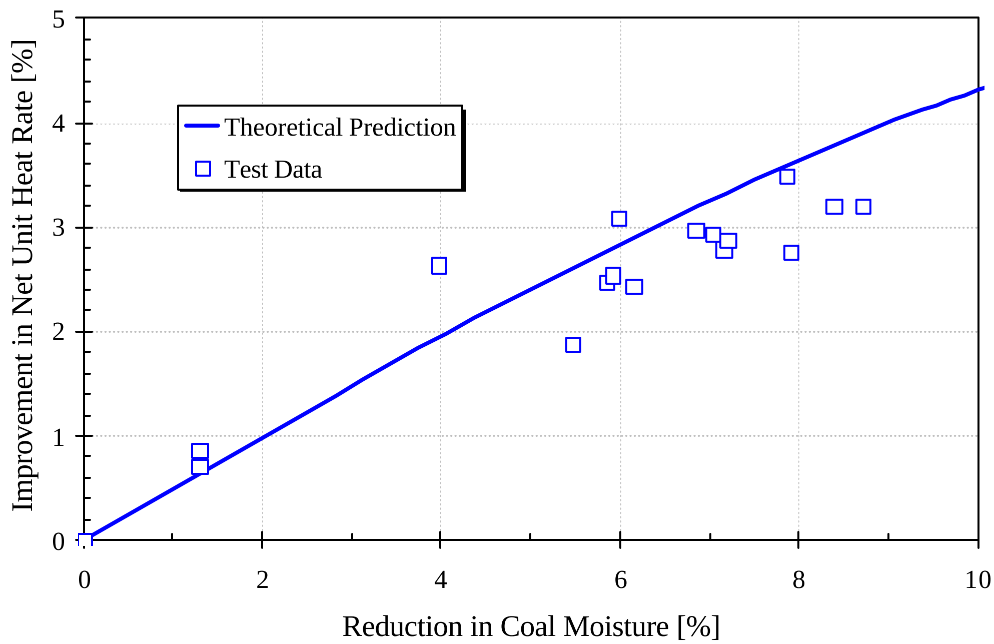


Figure 4: Improvement in Net Unit Heat Rate Versus Reduction in Coal Moisture Content

**This Investigation**

Theoretical analyses and coal test burns performed at a lignite fired power plant show that by reducing the fuel moisture, it is indeed possible to improve boiler performance and unit heat rate, reduce emissions and reduce water consumption by the evaporative cooling tower. The economic viability of the approach and the actual impact of the drying system on water consumption, unit heat rate and stack emissions will depend critically on the design and operating conditions of the drying system.

The present project is evaluating low temperature drying of lignite and Power River Basin (PRB) coal. Drying studies are being performed to gather data and develop models on drying kinetics. In addition, analyses are being carried out to determine the relative costs and performance impacts (in terms of heat rate, cooling tower water consumption and emissions) of the various drying options, along with the development of an optimized system design and recommended operating conditions.

The project is being carried out in five tasks:

**Task 1: Fabricate and Instrument Equipment**

Laboratory scale fixed bed and fluidized bed drying systems will be designed, fabricated and instrumented in this task.

**Task 2: Perform Drying Experiments**

The experiments will be carried out with both lignite and PRB coals, while varying superficial air velocity, inlet air temperature and specific humidity. In the fluid bed experiments, batch bed experiments will be run with different particle size distributions. The fixed bed experiments will include a range of coal top sizes. Bed depths will be varied for both the fixed and fluidized bed tests.

**Task 3: Develop Drying Models and Compare to Experimental Data**

In this task, the laboratory drying data will be compared to equilibrium and kinetic models to develop models suitable for evaluating tradeoffs between dryer designs.

**Task 4: Drying System Design**

Using the kinetic data and models from Tasks 2 and 3, dryers will be designed for 600 MW lignite and PRB coal-fired power plants. Designs will be developed to dry the coal by various amounts. Auxiliary equipment such as fans, water to air heat exchangers, dust collection system and coal crushers will be sized, and installed capital costs and operating costs will be estimated.

**Task 5: Analysis of Impacts on Unit Performance and Cost of Energy**

Analyses will be performed to estimate the effects of dryer operation on cooling tower makeup water, unit heat rate, auxiliary power, and stack emissions. The cost of energy will be estimated as a function of the reduction in coal moisture content. Cost comparisons will be made between dryer operating conditions (for example, coal particle feed size to fluidized beds and superficial air velocity for both fluidized bed and fixed bed dryers) and between dryer type.

The project was initiated on December 26, 2002. The project schedule is shown in Figure 5.

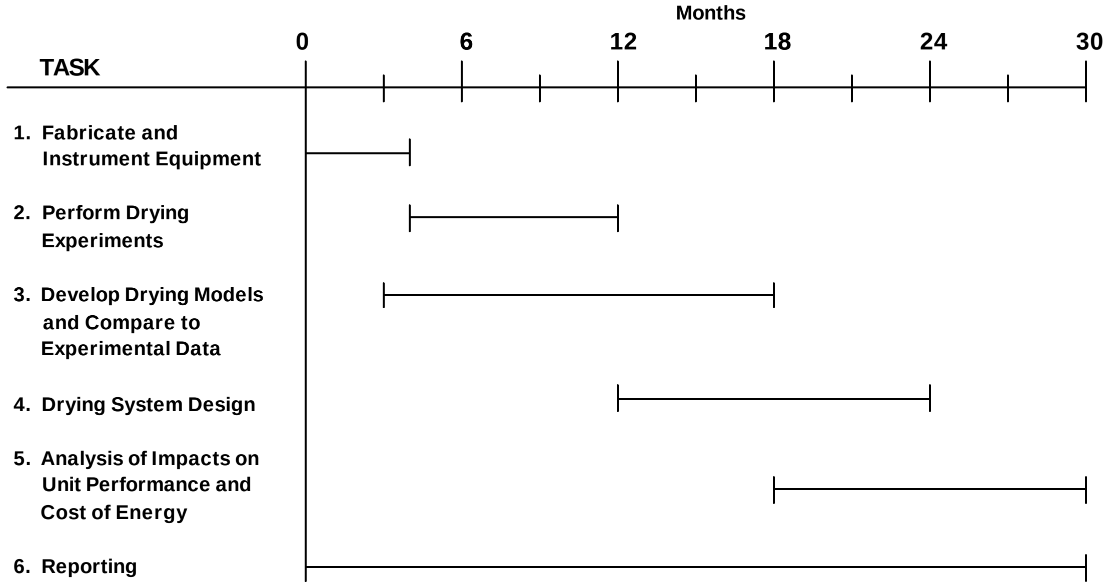


Figure 5: Project Schedule

## EXECUTIVE SUMMARY

### Background

Low rank fuels such as subbituminous coals and lignites contain relatively large amounts of moisture compared to higher rank coals. High fuel moisture results in fuel handling problems, and it affects station service power, heat rate, and stack gas emissions.

This project deals with lignite and subbituminous coal-fired pulverized coal power plants, which are cooled by evaporative cooling towers. The project involves use of the hot circulating cooling water leaving the condenser to provide heat needed to partially dry the coal before it is fed to the pulverizers.

Recently completed theoretical analyses and coal test burns performed at a lignite-fired power plant showed that by reducing the fuel moisture, it is possible to reduce water consumption by evaporative cooling towers, improve boiler performance and unit heat rate, and reduce emissions. The economic viability of the approach and the actual impact of the drying system on water consumption, unit heat rate and stack emissions will depend critically on the design and operating conditions of the drying system.

This project is evaluating alternatives for the low temperature drying of lignite and Power River Basin (PRB) coal. Laboratory drying studies are being performed to gather data and develop models on drying kinetics. In addition, analyses are being carried out to determine the relative costs and performance impacts (in terms of heat rate, cooling tower water consumption and emissions) of drying, along with the development of an optimized system design and recommended operating conditions.

### Results

A first principle drying model for a continuous flow fluidized bed dryer, operating at steady state conditions, was developed during this last Quarter. The model is based on conservation of mass and energy and empirical data on the equilibrium moisture content of the coal as a function of the temperature and relative humidity of the air as it leaves the fluidized bed. The model is written as a group of simultaneous ordinary differential equations which must be integrated numerically. Calculated results from the model were compared to lignite drying data obtained from a pilot plant-scale dryer located at Great River Energy's Coal Creek Station. Good agreement was obtained between the theoretical and measured results.

The first set of results were obtained from analyses to develop an optimized drying system design and determine the relative costs and performance impacts of drying lignite and PRB coals.

The first order impacts of firing dried lignite and PRB coals on fan and mill power, unit heat rate, boiler efficiency and coal, combustion air, and flue gas flow rates were determined. Simulations were carried out to determine the effects of dryer design and operating conditions on reduction in coal moisture and required in-bed heat transfer.

During the next Quarter, we plan to complete our experiments and simulations on the effects of inlet air moisture content on the drying process. We will perform additional experiments with PRB coal to expand the data base on drying kinetics with that fuel. Finally, we will continue the analyses on drying system design and on performance and cost impacts of coal drying.

## EXPERIMENTAL

Various laboratory test results on drying rates with lignite and PRB coals have been reported in previous Quarterly reports. Additional laboratory coal drying laboratory tests are in progress; and we plan to report results from these in the June 30, 2004 Quarterly Report.

## FIRST PRINCIPLE DRYING MODEL

### Computer Simulations for Continuously Operating Dryer

Previous results obtained at Lehigh in the laboratory batch dryer showed the fluidized bed is well mixed in the vertical direction, the air temperature leaving the dryer is equal to the bed temperature, and lignite drying rate can be accurately predicted using a system of differential equations involving conservation of mass and energy along with an empirical expression relating equilibrium coal moisture to bed temperature and relative humidity of the air leaving the bed. This same approach was used to derive a system of equations which describe drying in the continuous flow dryer shown schematically in Figure 6. Wet coal is fed to the bed at X=0. Some is elutriated near the feed point and is carried out of the bed by the fluidizing air. The remainder flows along the bed in the X direction and is discharged at X=L. Energy for drying is supplied by the elevated temperature of the fluidizing air and by a tube bundle carrying hot fluid which is immersed in the bed.

The resulting system of equations is given by

conservation of mass

$$\frac{d\Gamma}{d\xi} = -\frac{\dot{m}_{air}}{\dot{m}_{DC}}\left[\omega_2 - \omega_1\right] \qquad (1)$$

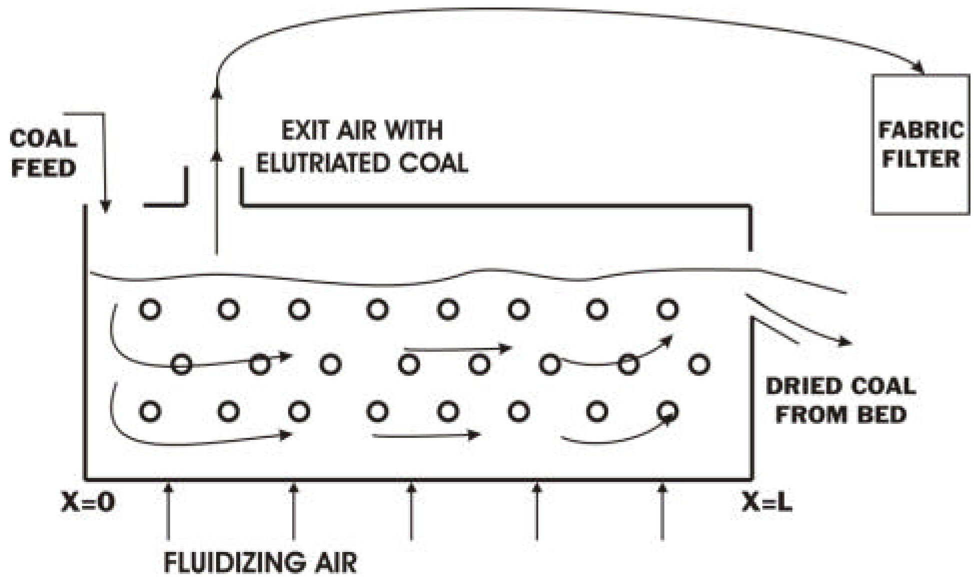


Figure 6: Sketch of Continuous Flow Dryer

conservation of energy

$$\frac{dT_2}{dx} = \left\{ h_L \frac{\dot{m}_{air}}{\dot{m}_{DC}} (w_2 - w_1) + \frac{Q_{TUBE}}{\dot{m}_{DC}} - \frac{\dot{m}_{air}}{\dot{m}_{DC}} \left[ Cp_a (T_2 - T_1) + w_2\, hg_2 - w_1\, hg_1 \right] \right\} / (C_C + GC_L) \tag{2}$$

where $\xi$ = X / L
- L = Length of Bed
- X = Horizontal Distance from Inlet of Bed
- $\dot{m}_{DC}$ = Mass Flow Rate of Dry Coal
- $\dot{m}_{air}$ = Mass Flow Rate of Dry Air
- ' = Coal Moisture Content on Dry Basis $[kg\ H_2O\ /\ kg\ dry\ coal]$
- $\omega$ = Specific Humidity
- $Q_{TUBE}$ = Rate of In-Bed Heat Transfer
- $T_1$ = Inlet Temperature of Air
- $T_2$ = Bed Temperature and Exit Air Temperature
- $\phi$ = Relative Humidity of Air Leaving Bed
- $Cp_a$; $C_c$; $C_L$ = Specific Heats
- $h_L$ = Enthalpy of Liquid $H_2O$

hg = Enthalpy of Saturated Vapor

subscript 1 = Air or Coal Entering Bed

subscript 2 = Air or Coal Leaving Bed

The relation between coal moisture and temperature and relative humidity of air leaving the bed $\Gamma = f(T_2 \log\phi)$ is given graphically in Figure 7 for North Dakota lignite.

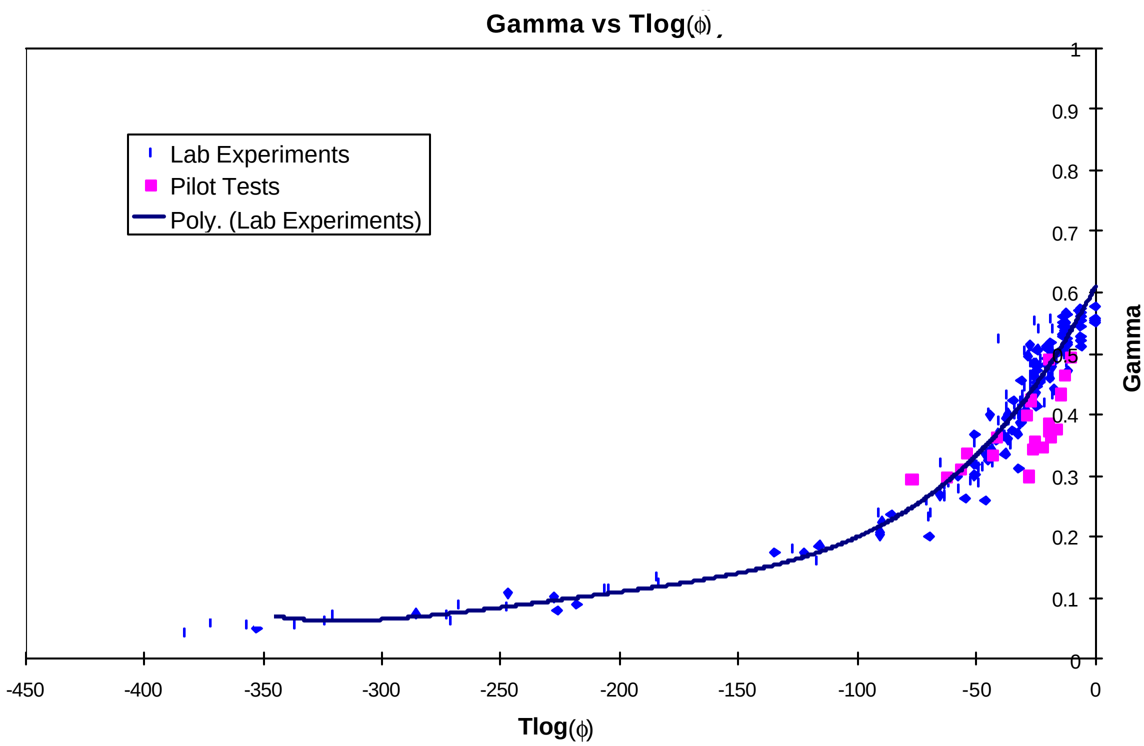


Figure 7: Equilibrium Coal Moisture Versus Tlog $\phi$ – North Dakota Lignite

Equations 1 and 2 show that for given values of inlet coal temperature and moisture level, and inlet air temperature and relative humidity, the solutions to the equations depend on $\frac{\dot{m}_{air}}{\dot{m}_{DC}}$ and $\frac{Q_{TUBE}}{\dot{m}_{DC}}$.

The term $\frac{Q_{TUBE}}{\dot{m}_{DC}}$ can also be written

$$\frac{Q_{TUBE}}{\dot{m}_{DC}} = U_o A_T \times DT_{avg} / \dot{m}_{DC}$$

where $U_o$ = Overall Heat Transfer Coefficient

$A_T$ = Tube Surface Area

$\Delta T_{avg}$ = Mean Temperature Difference Between In-Bed Coil and Bed

**Comparisons of Computer Model and Pilot Dryer Data**

A computer program was written to solve Equations 1 to 2, and this was used to simulate various drying tests performed at Great River Energy's Coal Creek Station. These tests were run in a pilot scale lignite dryer with a nominal coal drying capacity of 30 kg/minute. Temperatures of fluidizing air and the in-bed tube bundle range from 50 to 70°C. Figures 8 to 23 show the results for four cases, which represent the range of test conditions (see Table 1).

**Table 1**

**Test Conditions for Tests 4, 20, 23 and 30**

| TEST# | $T_{COAL\ IN}$ (°C) | $T_{air1}$ (°C) | $M_{Air}$ (Kg/min) | $M_{DC,\ FEED}$ (Kg/min) | $G_1$ (Kg $H_2O$/ Kg dry coal) | $Q_{TUBE}$ (W) |
|---|---|---|---|---|---|---|
| 4 | 30.3 | 49.4 | 184.2 | 15.5 | 0.401 | 0 |
| 20 | 18.4 | 72.1 | 169.6 | 22.5 | 0.440 | 85389 |
| 23 | 22.0 | 71.6 | 182.3 | 14.1 | 0.488 | 71902 |
| 30 | 20.9 | 71.1 | 172.4 | 27.2 | 0.427 | 85389 |

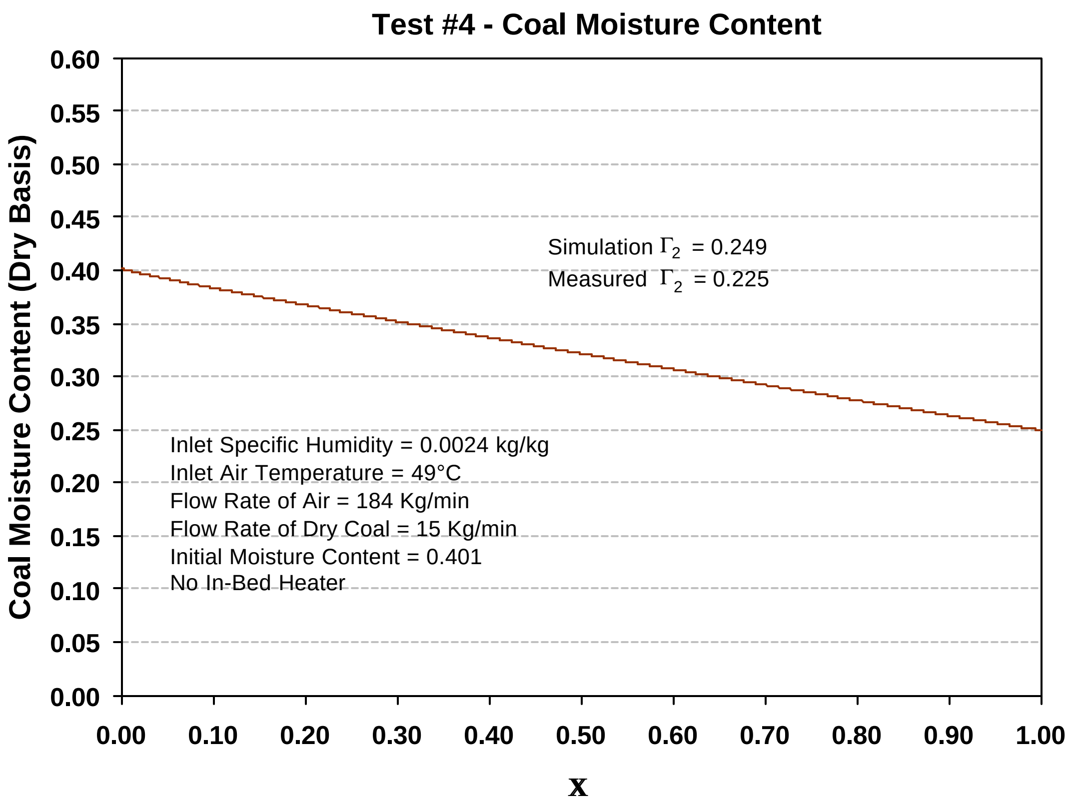


Figure 8: Axial Variation of Coal Moisture Content for Test #4

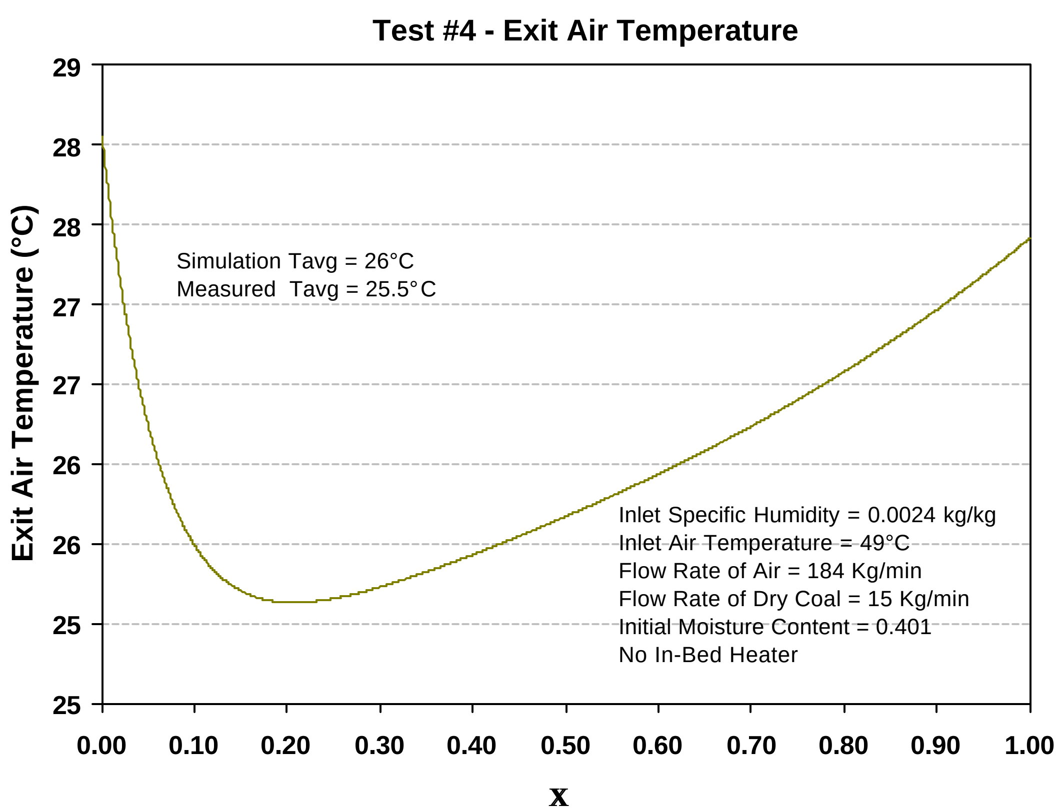


Figure 9: Axial Variation of Bed Temperature and Exit Air Temperature for Test #4

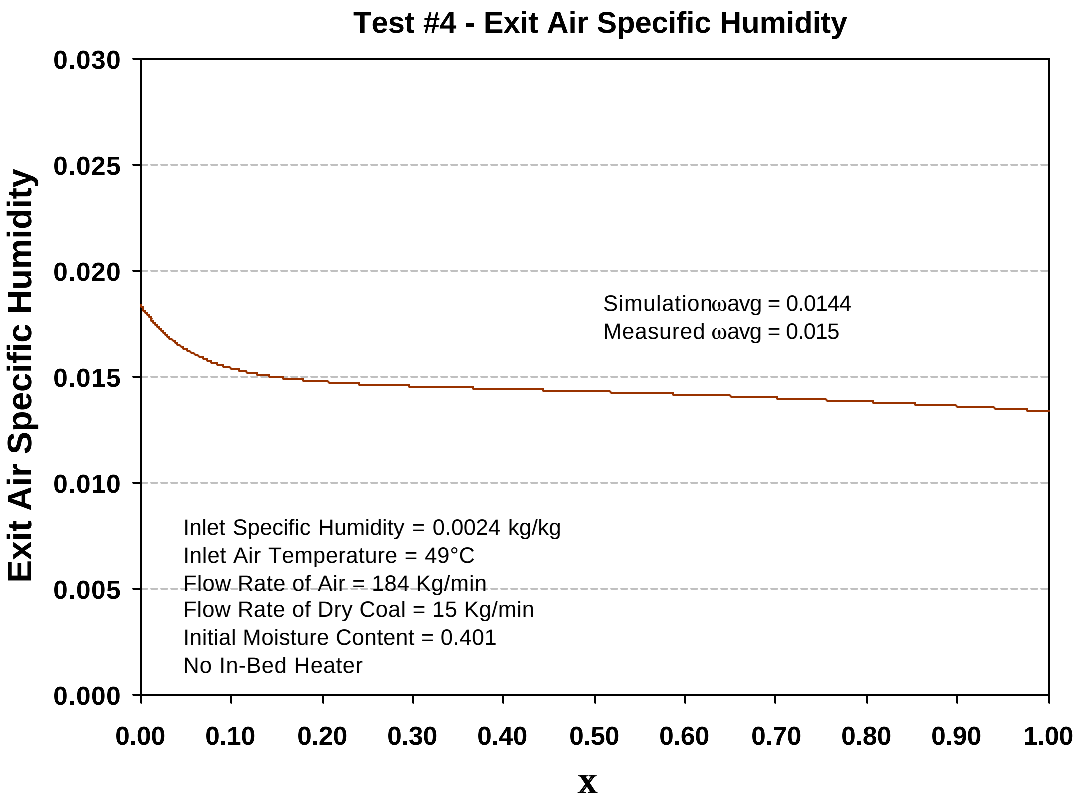


Figure 10: Axial Variation of Exit Air Specific Humidity for Test #4

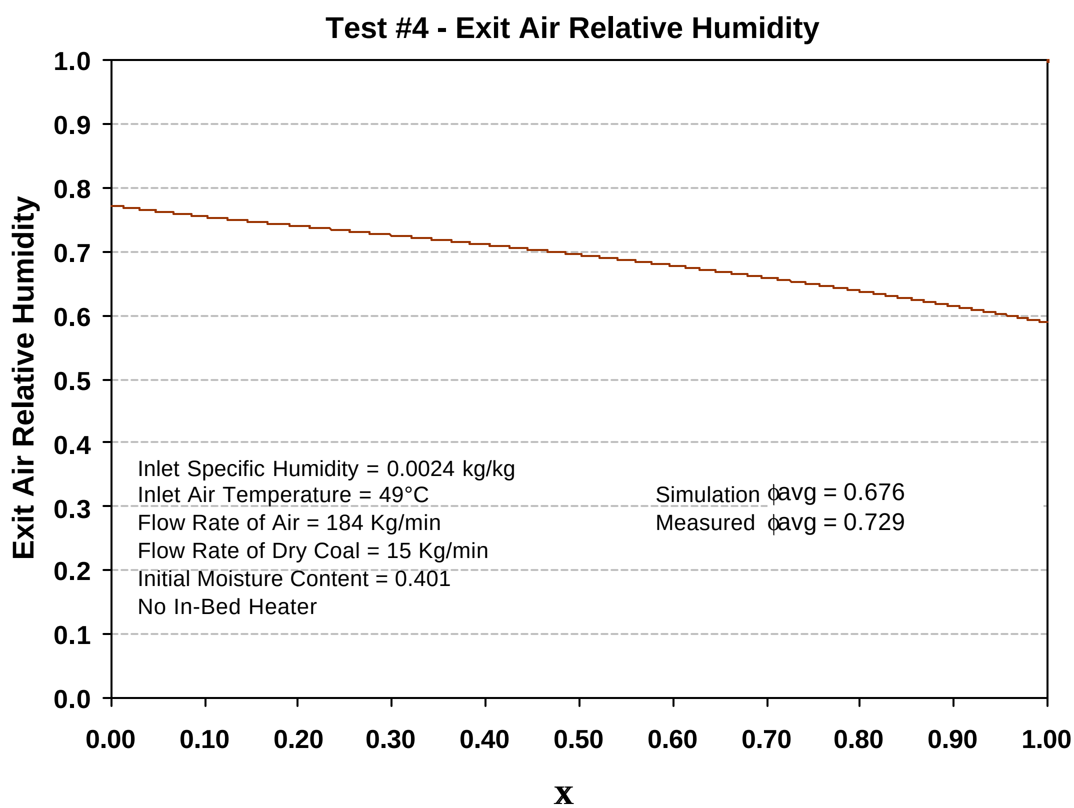


Figure 11: Axial Variation of Exit Air Relative Humidity for Test #4

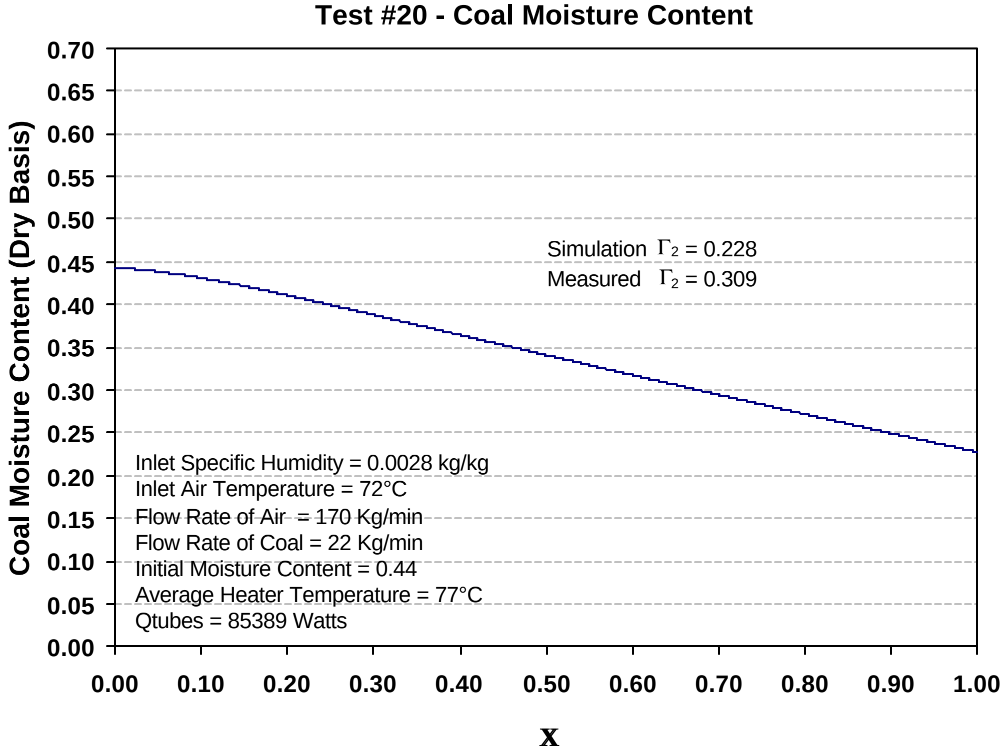


Figure 12: Axial Variation of Coal Moisture Content for Test #20

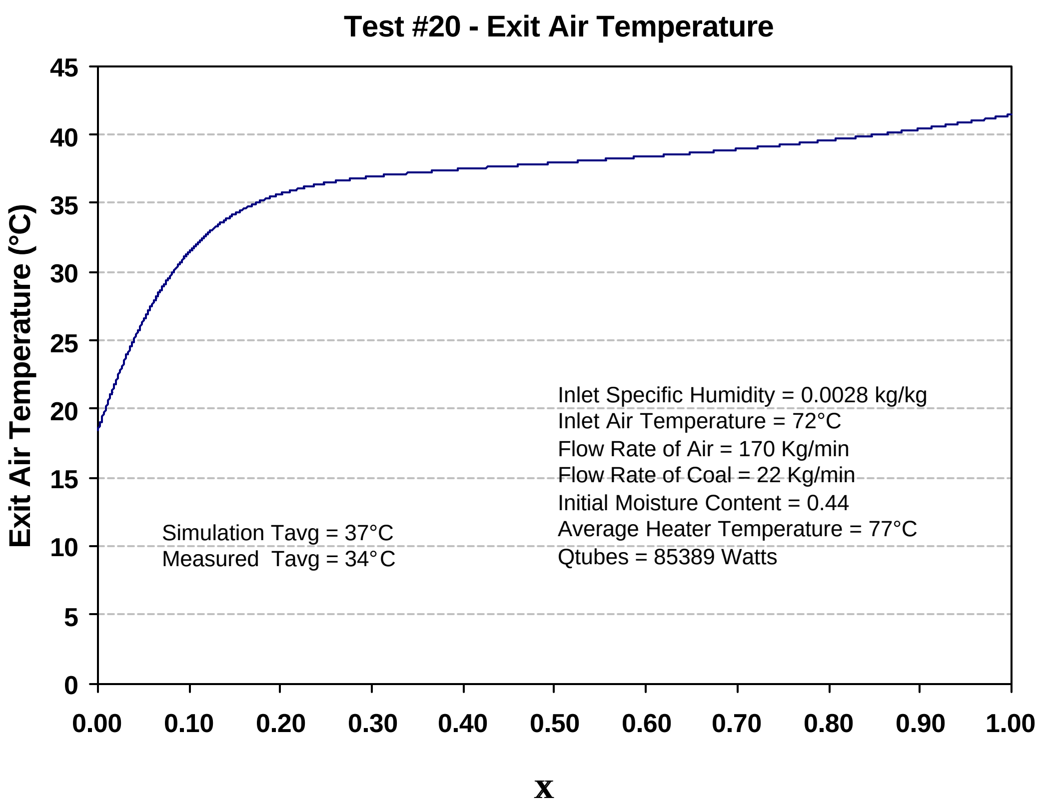


Figure 13: Axial Variation of Bed Temperature and Exit Air Temperature for Test #20

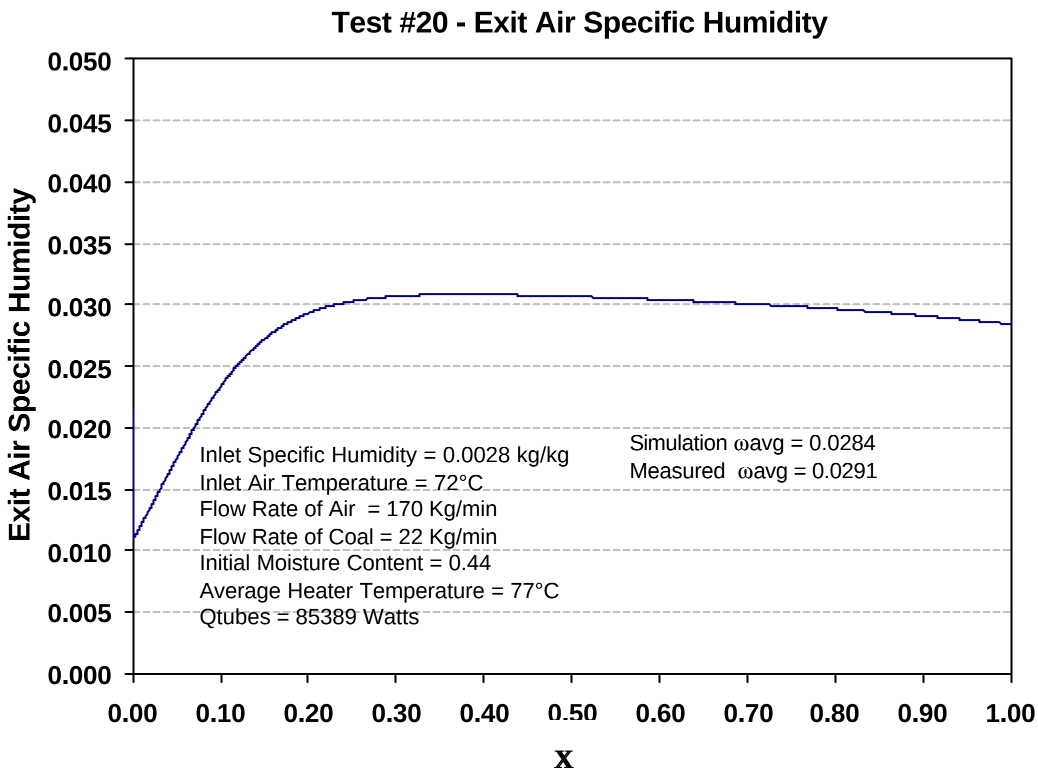


Figure 14: Axial Variation of Exit Air Specific Humidity for Test #20

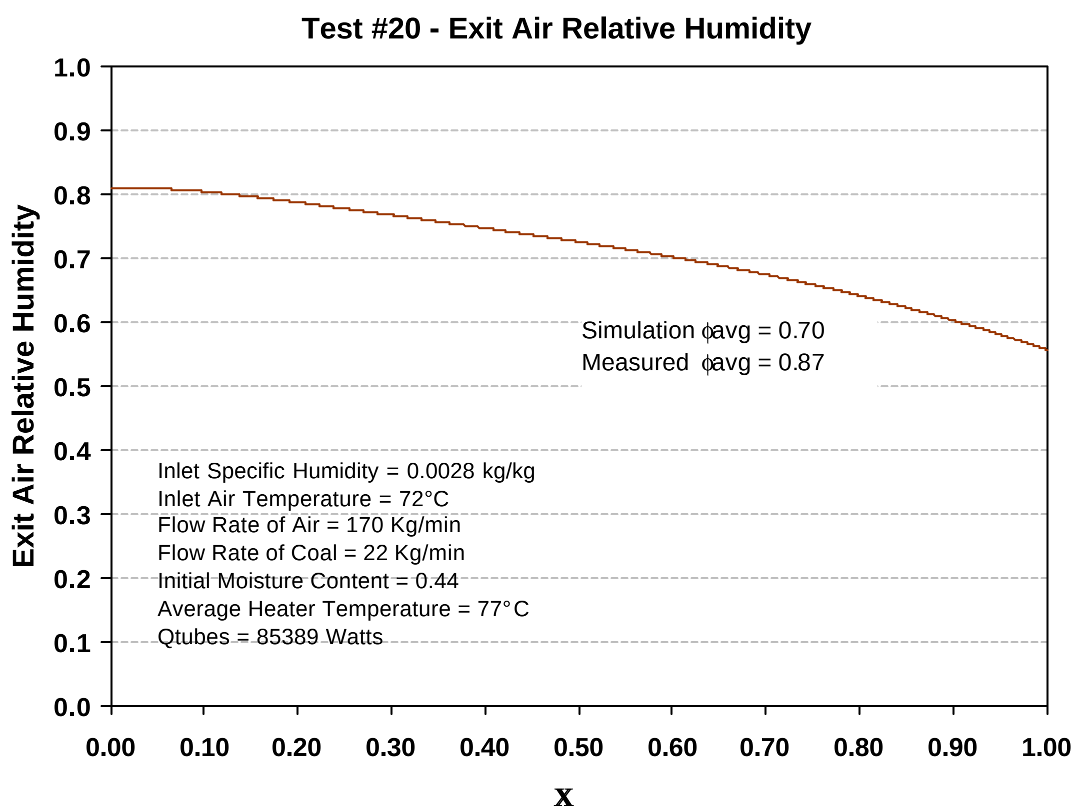


Figure 15: Axial Variation of Exit Air Relative Humidity for Test #20

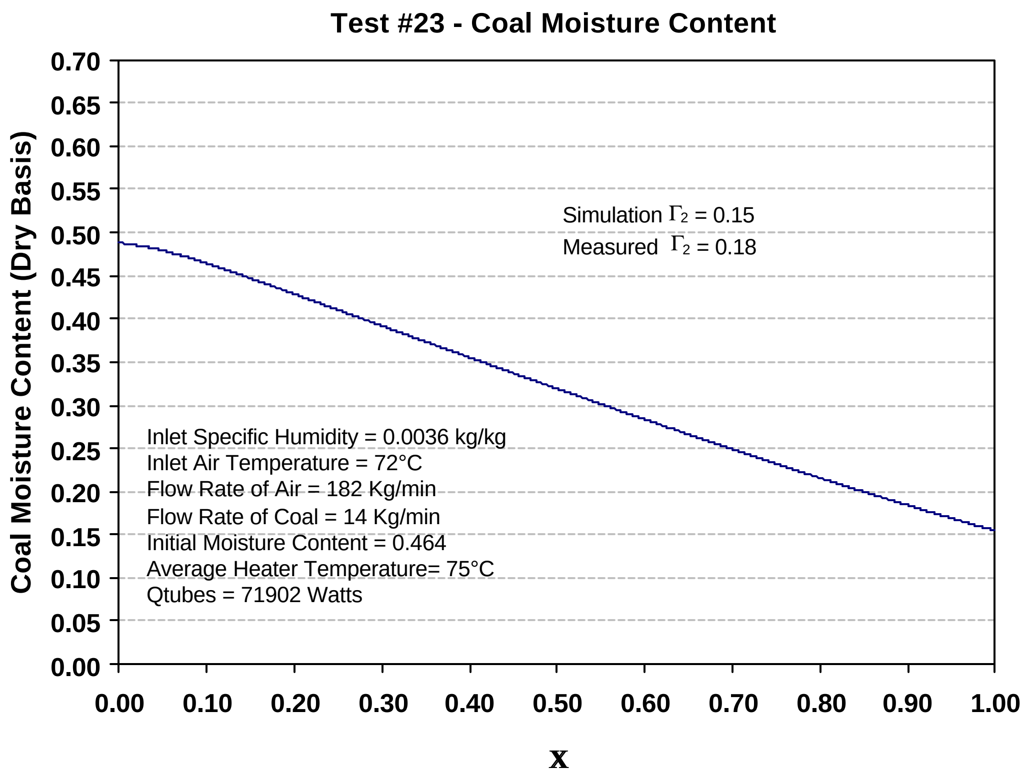


Figure 16: Axial Variation of Coal Moisture Content for Test #23

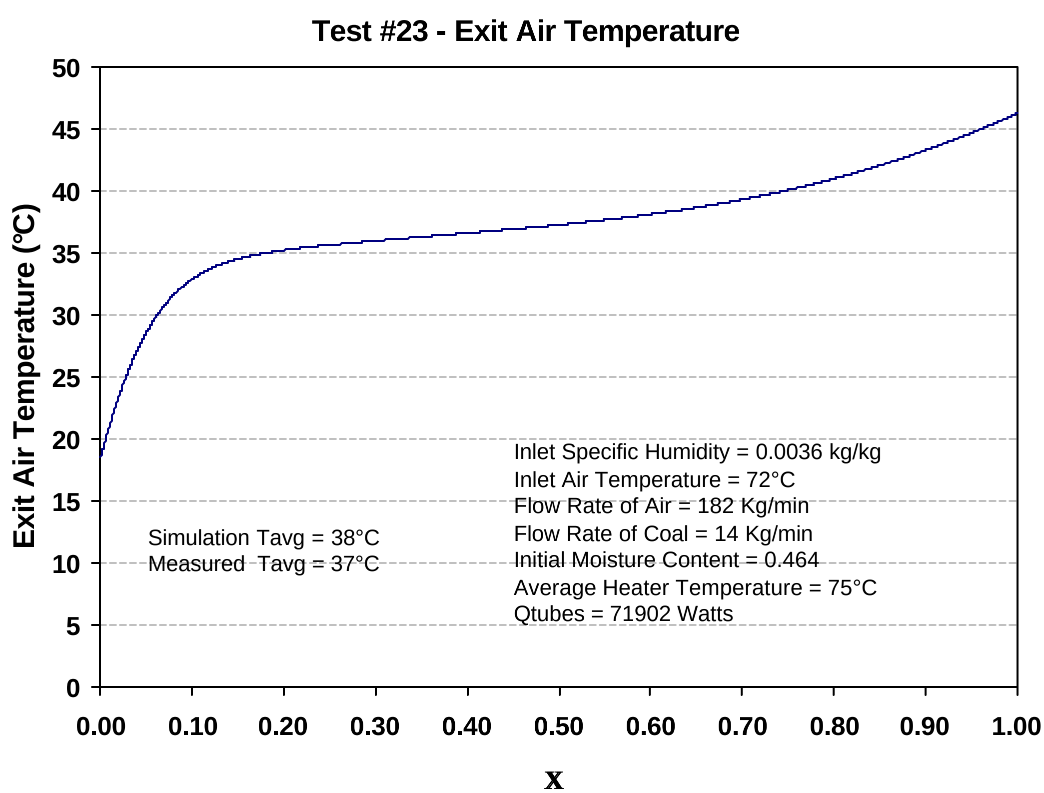


Figure 17: Axial Variation of Bed Temperature and Exit Air Temperature for Test #23

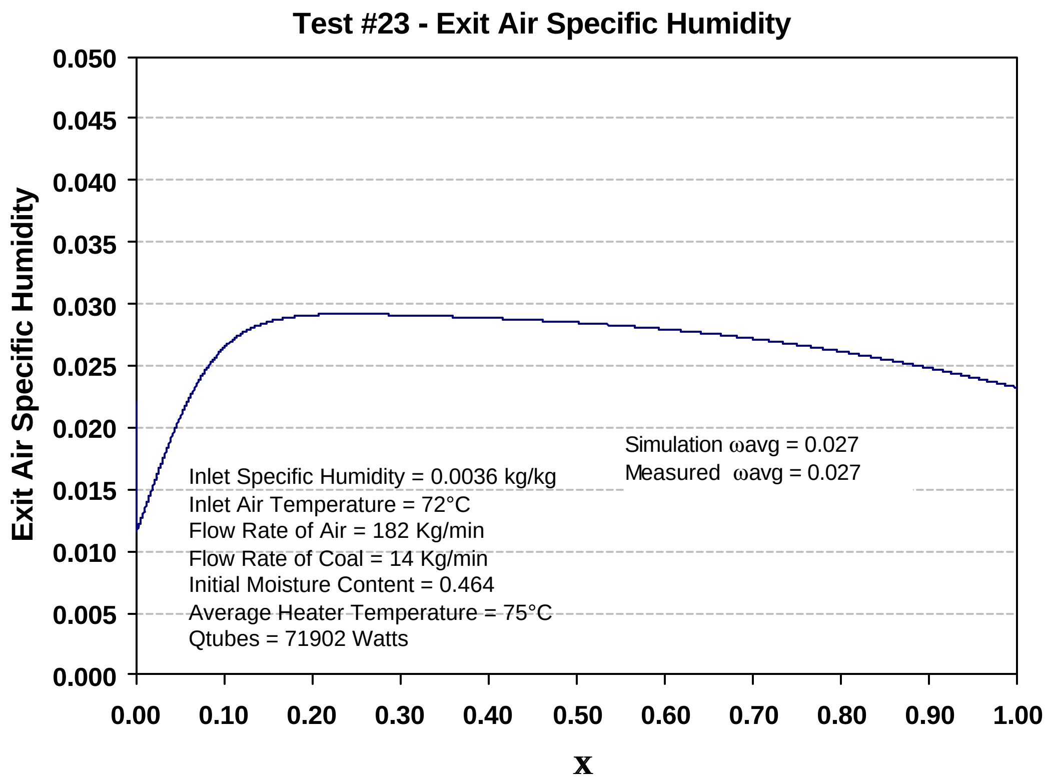


Figure 18: Axial Variation of Exit Air Specific Humidity for Test #23

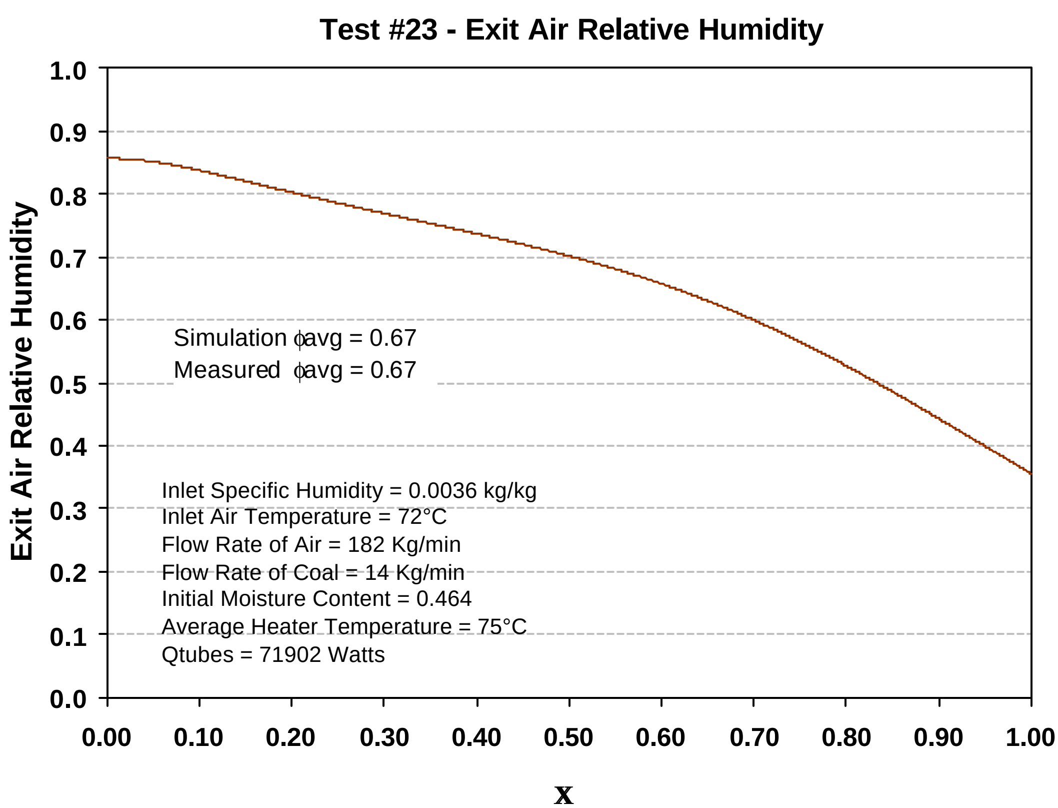


Figure 19: Axial Variation of Exit Air Relative Humidity for Test #23

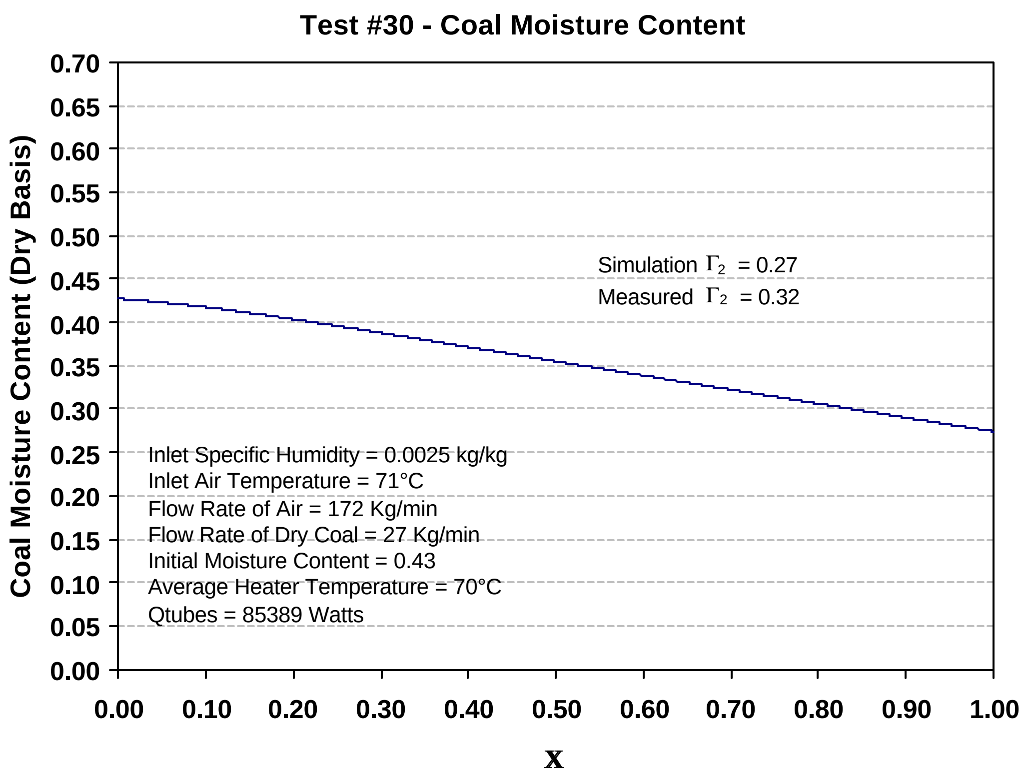


Figure 20: Axial Variation of Coal Moisture Content for Test #30

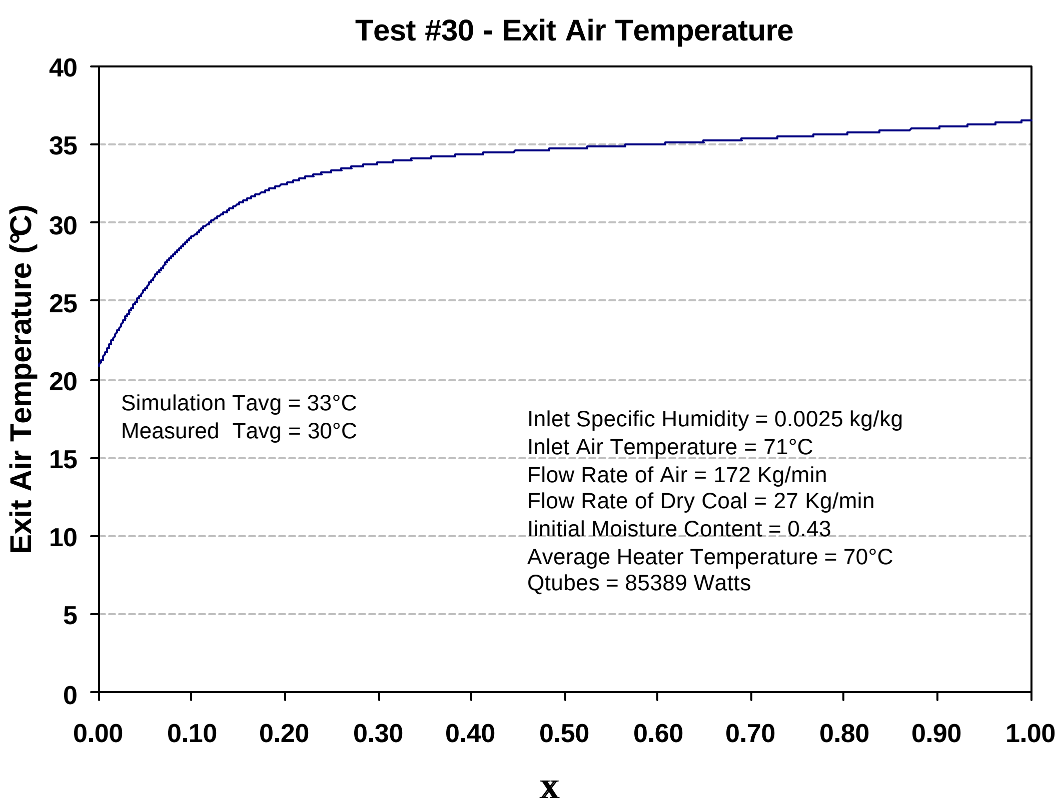


Figure 21: Axial Variation of Bed Temperature and Exit Air Temperature for Test #30

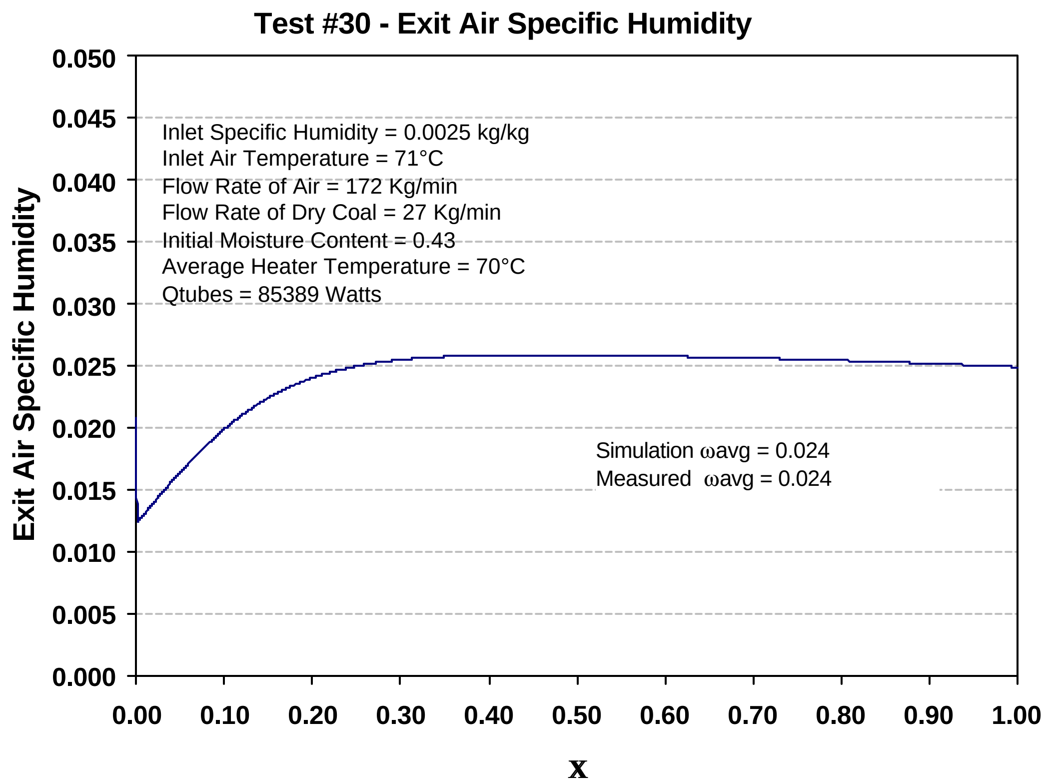


Figure 22: Axial Variation of Exit Air Specific Humidity for Test #30

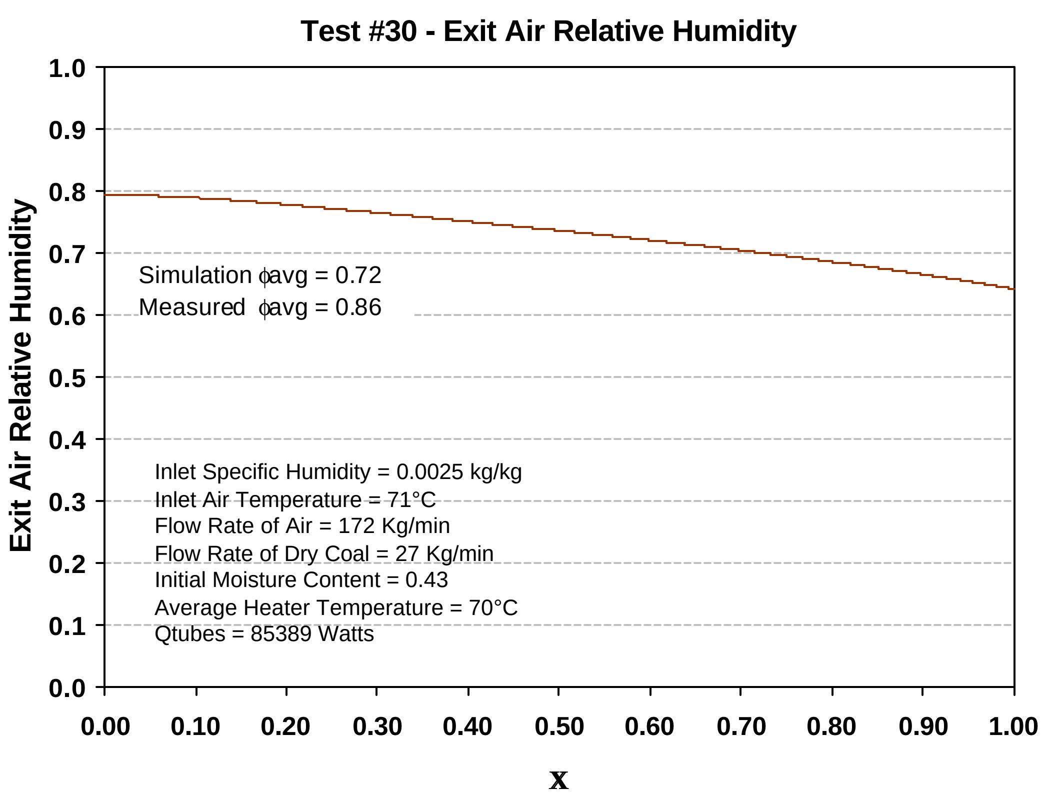


Figure 23: Axial Variation of Exit Air Relative Humidity for Test #30

Figures 8 to 23 show the axial variations of coal moisture from dryer inlet, X=0, to dryer exit, X=L, (or from $\xi = 0$ to $\xi = 1$), air temperature leaving bed, and specific humidity and relative humidity of air leaving the bed. The coal flow rate used in these calculations is 90 percent of the coal flow rate fed to the bed, the remaining 10 percent is assumed to have been carried from the bed by elutriation near the coal feed point at $\xi = 0$.

The results show, for this range of drying conditions, coal moisture content, $\Gamma$, decreased nearly linearly with $\xi$, the exit air temperature increased with $\xi$ after an initial adjustment for the inlet temperature of the coal, the relative humidity of exit air decreased with $\xi$, and the specific humidity either increased or decreased depending on axial variations in temperature and relative humidity.

Table 2 compares the measured and predicted results for these four cases. Since the measurements for temperature and humidity are average values obtained from sensors in a duct downstream of the bed, the average values from the computer simulations were obtained by integrating air temperature and specific humidity from $\xi = 0$ to $\xi = 1$. The computed average values of relative humidity, $\phi$, were obtained from the computed average values of $T_{air}$ and $\omega$, using a psychrometric chart.

**Table 2**

**Comparison of Predicted and Measured Performance for Tests 4, 20, 23 and 30**

| TEST | $G_1 - G_2$ | | $T_{air2}$ (avg) °C | | $\omega_2$ (avg) | | $\phi_2$ (avg) % | |
|---|---|---|---|---|---|---|---|---|
| | Measured | Predicted | Measured | Predicted | Measured | Predicted | Measured | Predicted |
| 4 | 0.175 | 0.151 | 25.5 | 26.0 | 0.0150 | 0.0144 | 72.5 | 68 |
| 20 | 0.134 | 0.217 | 33.5 | 36.7 | 0.0291 | 0.0284 | 86.89 | 70 |
| 23 | 0.300 | 0.335 | 36.9 | 37.8 | 0.0273 | 0.0276 | 66.7 | 67 |
| 30 | 0.107 | 0.150 | 30.2 | 33.3 | 0.0237 | 0.0242 | 86.1 | 72 |

Comparisons for all of the test runs are given in Figures 24 to 27. Figure 24 compares predicted and measured values of $\Gamma_1 - \Gamma_2$. The scatter in the data in Figure 24, probably reflects random sampling errors in both the $\Gamma_1$ and $\Gamma_2$ measurements.

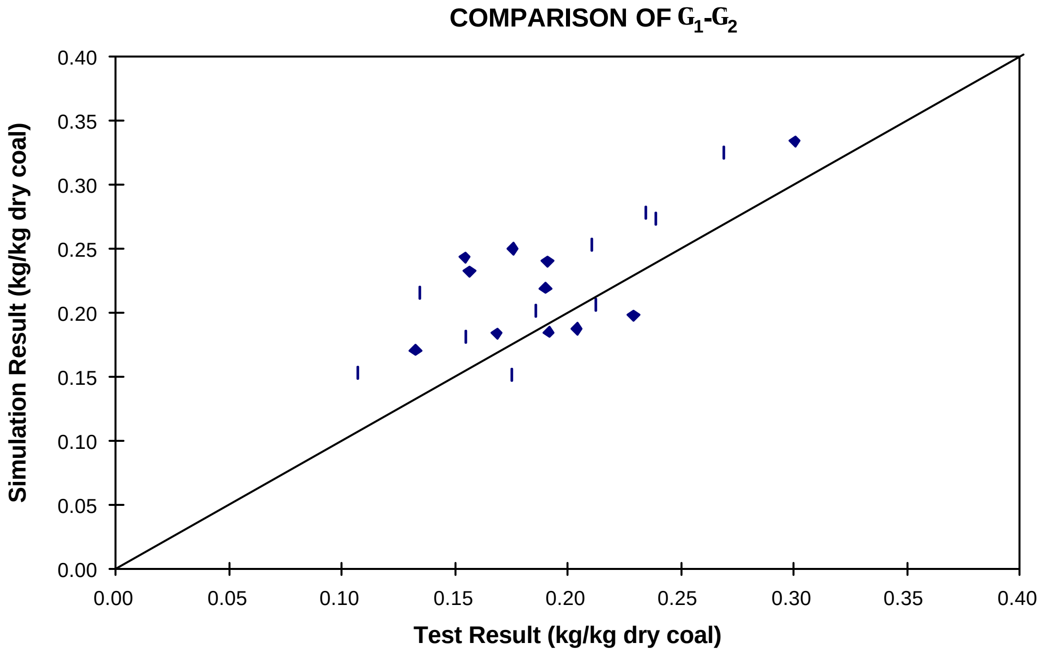


Figure 24: Comparison of Predicted Versus Measured Values – Change in Coal Moisture, ($\Gamma_1$ - $\Gamma_2$).

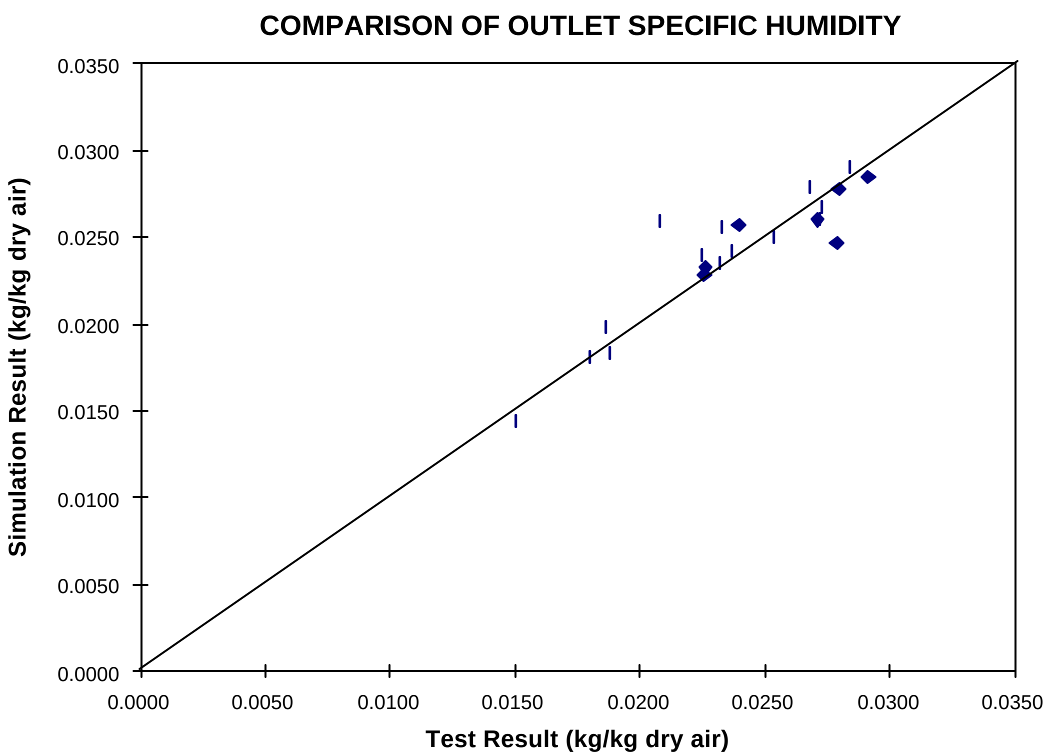


Figure 25: Comparison of Predicted Versus Measured Values – Average Outlet Specific Humidity

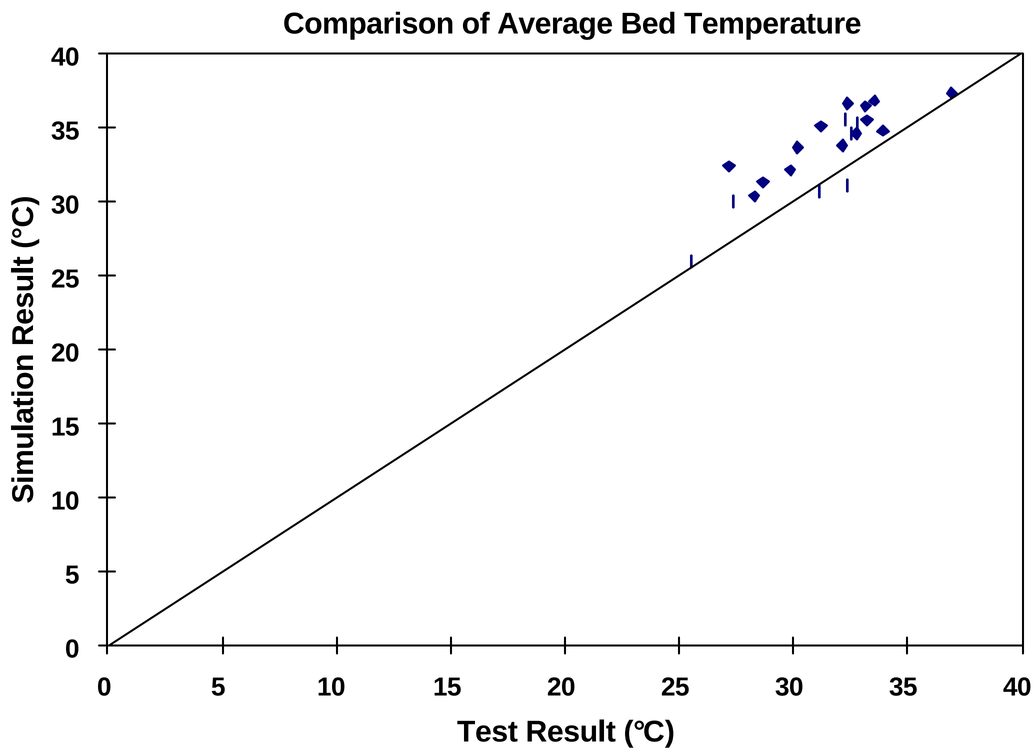


Figure 26: Comparison of Predicted Versus Measured Values – Average Bed Temperature and Exit Air Temperature

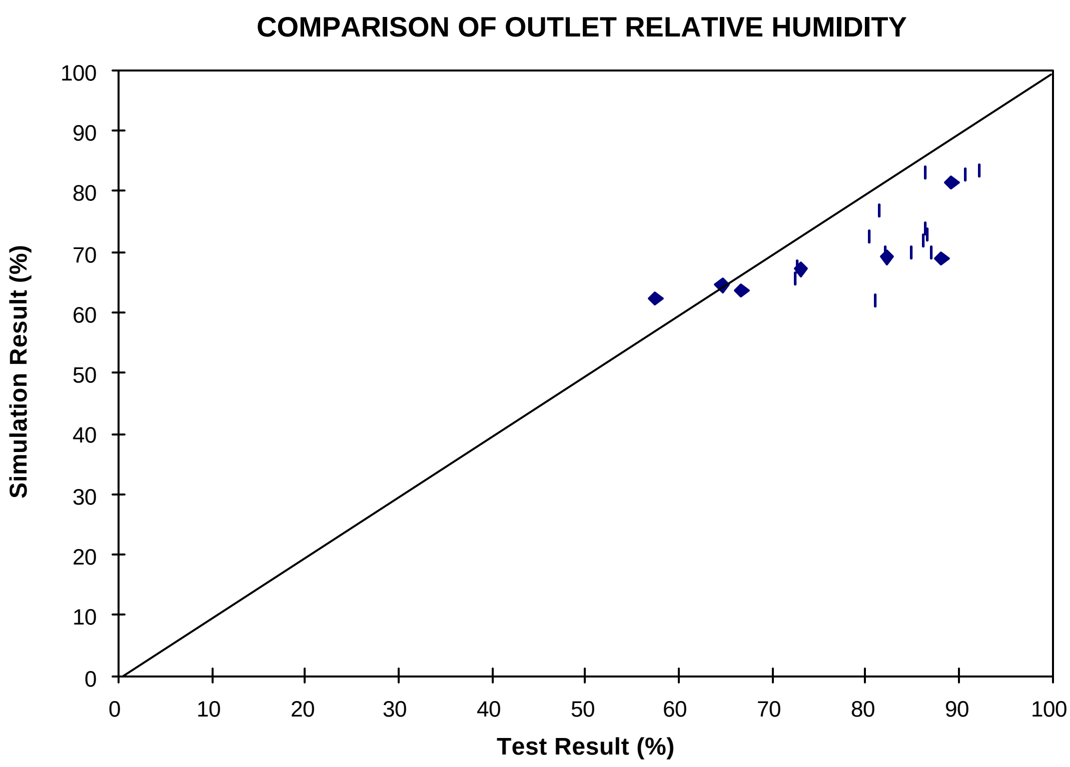


Figure 27: Comparison of Predicted Versus Measured Values – Average Outlet Relative Humidity

In addition to random error, Figure 24 also shows a bias error, with the predicted values of $\Gamma_1$ - $\Gamma_2$ being larger than the measured values by 10 to 15 percent.

Figure 25, which compares measured to predicted specific humidity, shows excellent agreement between the two. Figures 26 and 27 indicate that, on average, the measured and predicted values of bed temperature differ by about 2.5°C and, on average, the measured and predicted values of relative humidity of the air leaving the bed differ by about 10 percent.

## DRYING SYSTEM DESIGN AND ANALYSIS OF IMPACTS ON UNIT PERFORMANCE AND COST OF ENERGY

Tasks 4 and 5 involve the design of drying systems for 600 MW lignite and PRB coal-fired power plants, analysis of the effects of dryer operation on cooling tower makeup water, unit heat rate, auxiliary power and stack emissions, and estimation of the cost of energy as a function of reduction in coal moisture content and dryer design. The work in these two tasks is progressing in the following subtasks:

Subtask 1: Estimate effects of firing dried coal on flow rates of combustion air and flue gas, required feed rate of coal to boiler, mill and fan power, boiler efficiency and unit heat rate.

Subtask 2: Estimate required dryer size, flow rates of fluidizing air and amount of in-bed heat transfer as functions of drying temperature and coal product moisture.

Subtask 3: Integrate dryer into boiler and turbine cycle and calculate overall impacts on heat rate, evaporative cooling tower makeup water and emissions.

Subtask 4: Size remaining components and develop drying system cost estimates.

Subtask 5: Perform calculations to select optimal drying system configuration and product coal moisture.

During this last Quarter, the effort was focused on Subtasks 1 and 2. A brief description of the work done so far is given below.

**Impact of Firing Dried Coal on Boiler Operating Parameters**

This subtask involves an analysis of the effects of firing dried coal on unit operating parameters, such as flow rates of combustion air and flue gas, feed rate of coal to the boiler, mill and fan power, boiler efficiency and unit heat rate. The calculation method used involves mass and energy balances around different parts of the unit, combined with data on component performance as a function of operating conditions.

The analysis for both lignite and PRB coals assumes a net generation of 600MW and full load operation. The unit design, which is similar to that of Great River Energy's Coal Creek Station, is referred to here as the "Baseline" design (see Figure 28). The balanced draft boiler is equipped with a trisector air preheater. Steam coils at the inlets to the forced draft (FD) and primary air (PA) fans, use turbine cycle extraction steam to preheat the air before it enters the fans. A baseline net unit heat rate of 10,000 Btu/kWh is assumed with lignite. At this stage of the analysis, it is assumed the coal is dried off-site with no performance penalties assessed against the power plant or performance enhancements credited to the power plant for the drying process.

Figure 29 shows the lignite and PRB flow rates to the pulverizers required to generate 600 MW of electricity. The coal moisture, expressed on a wet basis, at the pulverizer inlets ranges from maximum values of 40% for lignite and 30% for PRB for no

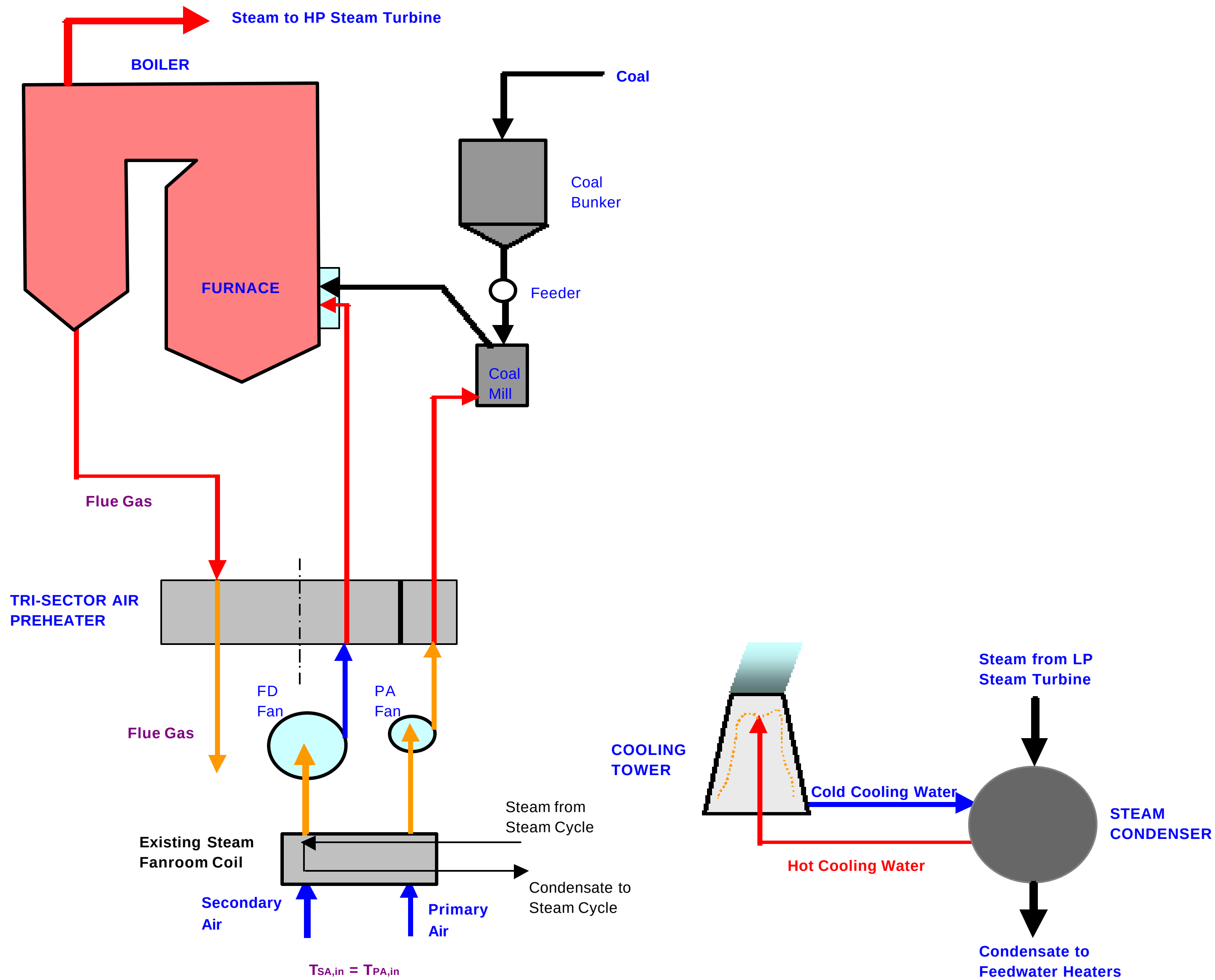


Figure 28: Baseline Design

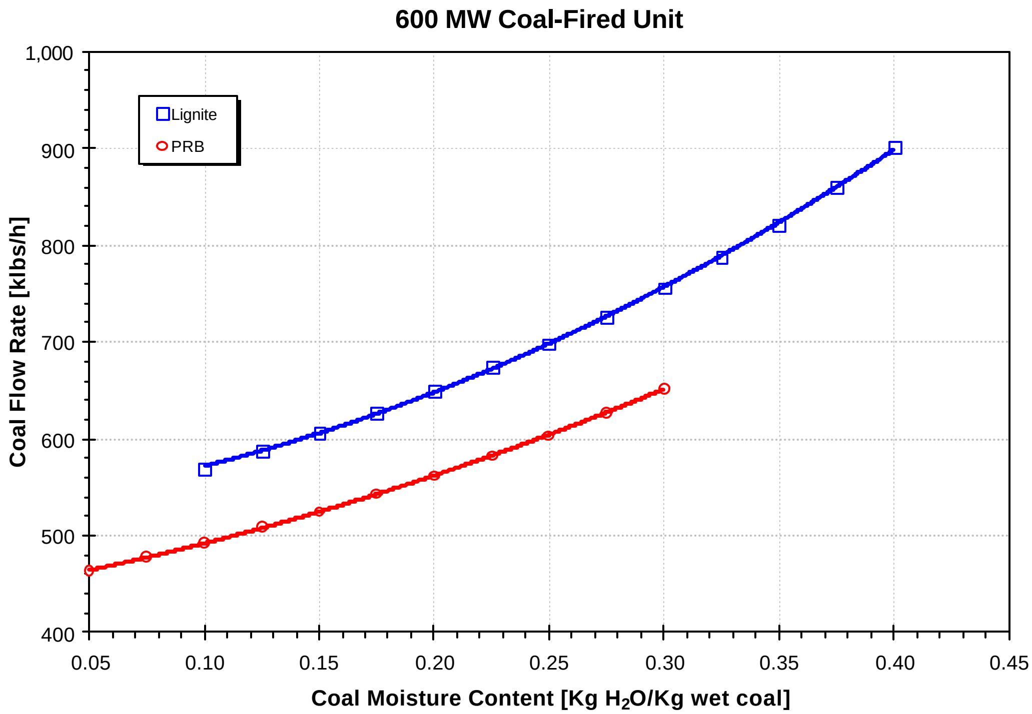


Figure 29: Variation of Required Coal Feed Rate with Coal Moisture Content

drying to lower levels with drying. The reductions in required coal flow rate with a reduction in coal moisture content reflect the reduced coal moisture and an improvement in unit heat rate.

Firing a lower moisture coal results in a reduction in station service power due to reduced fan and pulverizer power requirements. Figures 30 and 31 show how the combustion air and flue gas flow rates vary with coal moisture content, while Figure 32 gives fan and mill power versus coal moisture. While the induced draft (ID) and primary air (PA) fan power requirements are lower for a dryer coal due to lower primary air and flue gas flow rates, the flow rate of the air through the forced draft (FD) fan increases, resulting in larger FD power for lower moisture content. Finally, Figures 33 and 34 show how boiler efficiency and net unit heat rate vary with the moisture content of the coal fed to the pulverizers.

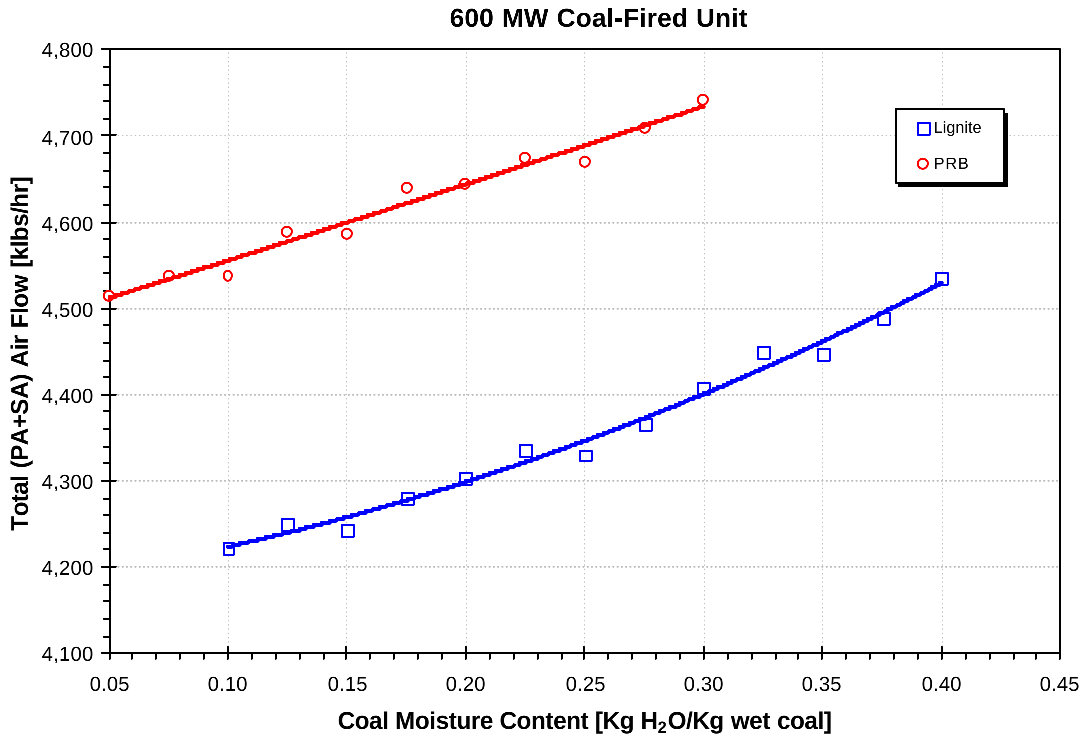


Figure 30: Effect of Coal Moisture on Air Flow Rates

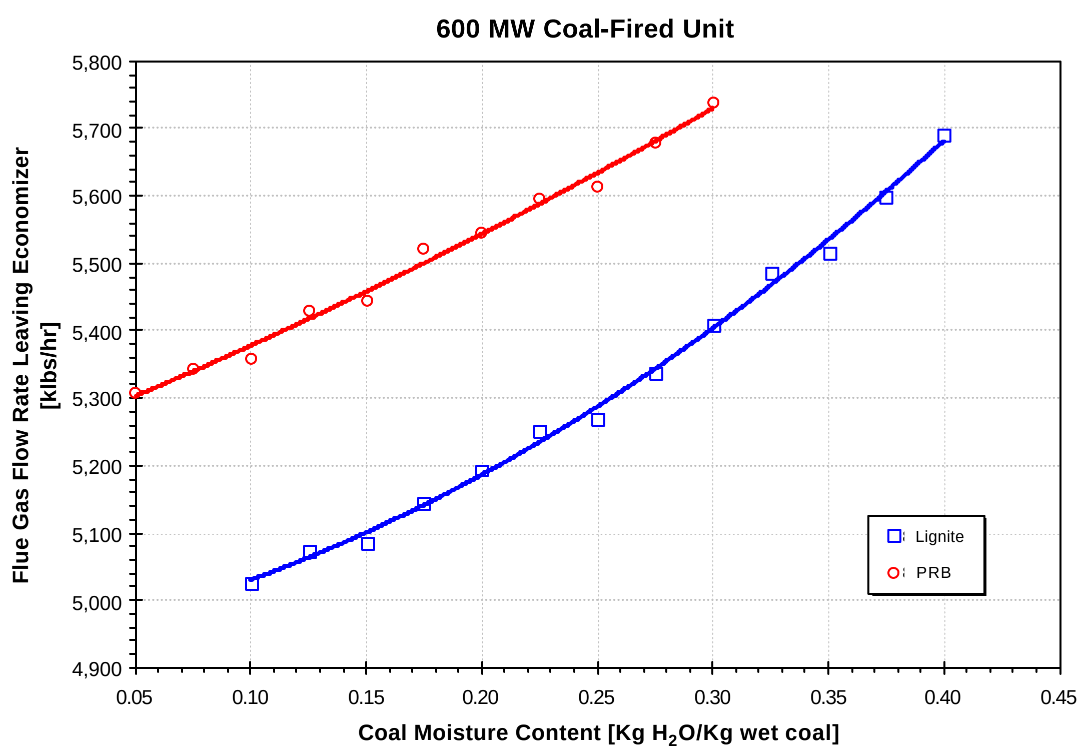


Figure 31: Effect of Coal Moisture on Flue Gas Flow Rate

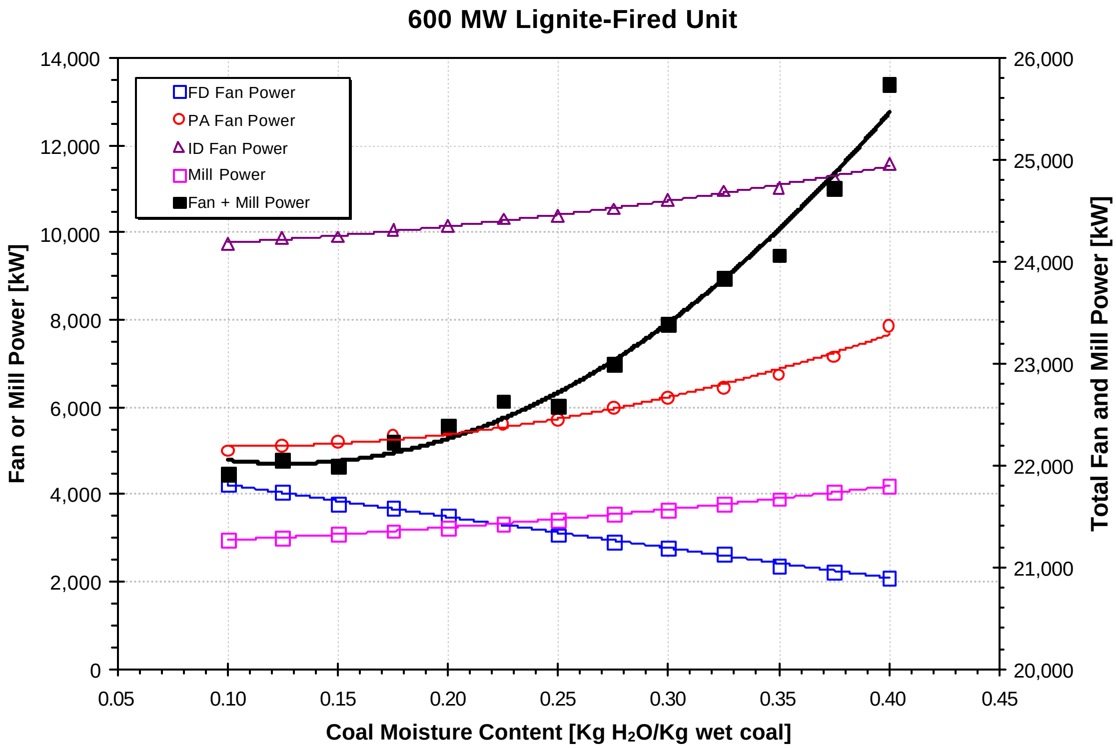


Figure 32: Effect of Coal Moisture on Fan and Mill Power

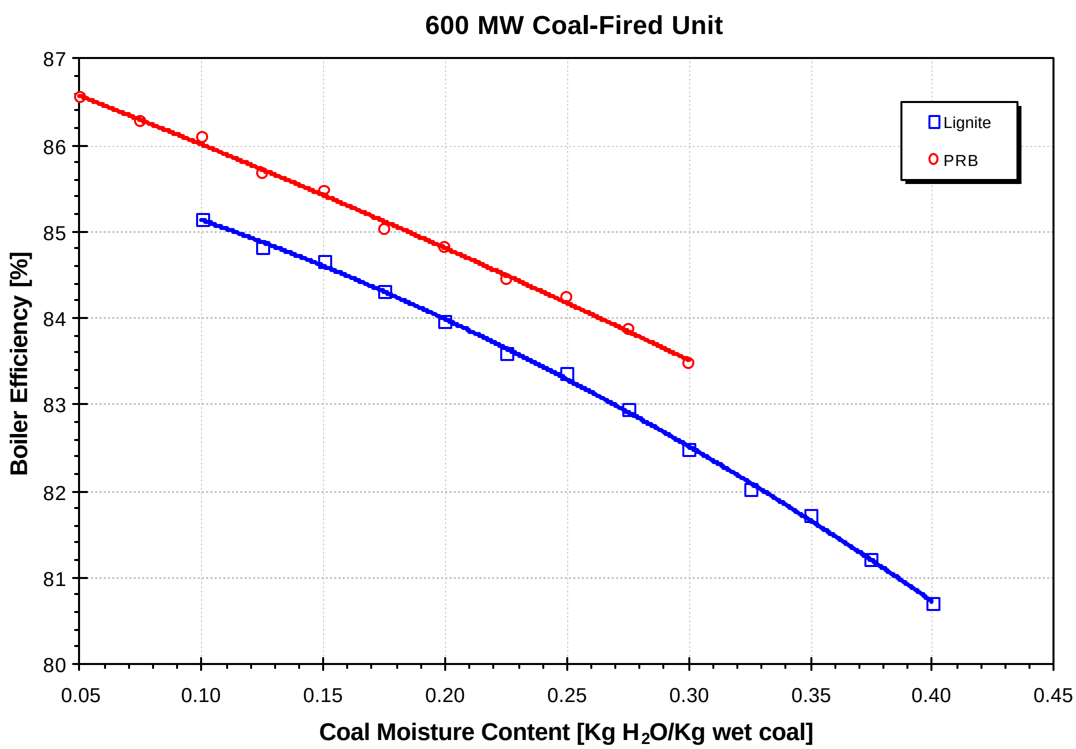


Figure 33: Effect of Coal Moisture on Boiler Efficiency

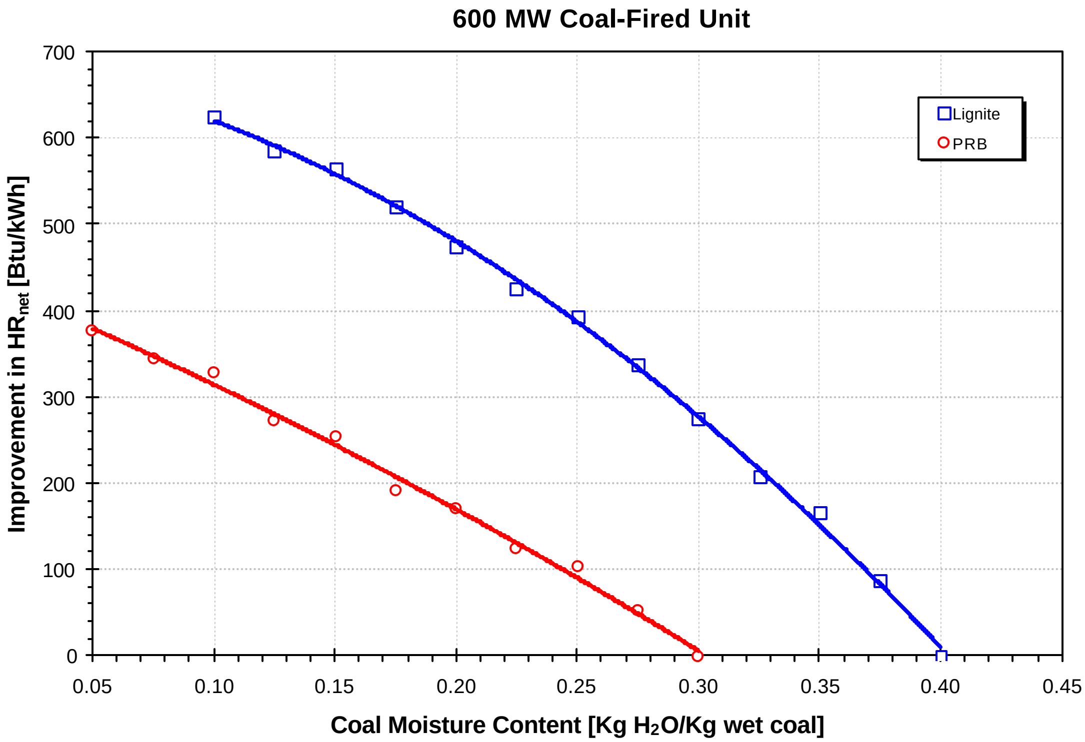


Figure 34: Effect of Coal Moisture on Net Unit Heat Rate

## Dryer Design Parameters for Lignite Firing

This subtask involves calculations of commercial scale dryer performance as a function of dryer design and process conditions. The analysis assumes one dryer per pulverizer, which requires the dryer to handle a lignite feed rate of approximately 70,000 kg/hr, which is typical of the capacity of a large pulverizer with lignite. The laboratory drying tests were all performed with a coal feed, having a 6.35 mm top size and this required fluidization velocities of approximately 1.1 m/s (based on standard temperature and pressure) to achieve good quality fluidization. The design calculations performed in this task are based on the same value of $U_0$. The combination of distributor surface area and expanded bed depth constrains the maximum tube surface area of the in-bed tube bundle, and the distributor surface area fixes the required flow rate of fluidizing air. Bed depth is likewise constrained by bed pressure drop considerations. Based on these considerations, the first round of dryer performance calculations was based on the following bed design and process conditions:

| | |
|---|---|
| Coal Flow Rate | 68,100 Kg/hr |
| Air Flow Rate | 30 to 545 Kg/s |
| Bed Depth | 1.02 to 1.27 m |
| Superficial Air Velocity | 1.1 m/s |

The in-bed tube bundle was assumed to be made of horizontal 2.54 cm OD tubes, placed in a staggered array, with a 5.08 cm horizontal and a 4.45 cm vertical center-to-center pitch. The resulting distributor and tube surface areas and total number of in-bed tubes are shown in Figures 35 and 36 as functions of flow rate of fluidization air.

All of the dryer performance calculations were carried out with the dryer computer code described in an earlier section of this report. Sample calculations are shown in Figures 37 to 39 for an inlet lignite moisture of 0.63 Kg $H_2O$/Kg dry coal. The results illustrate how the coal moisture, bed temperature and specific humidity of the exit air vary with distance from the bed inlet and with air flow rate. For this range of conditions, the coal moisture decreases nearly linearly, the bed temperature increases, and the specific humidity of the air leaving the bed increases and then approaches an asymptote with distance from the coal feed point.

Additional calculations were performed to determine how the exit coal moisture (Kg $H_2O$/Kg wet coal), varies with average temperature of the in-bed heat exchanger, inlet air temperature and bed depth (Figure 40). The corresponding in-bed heat transfer is shown in Figure 41.

**CONCLUSIONS**

A first principle drying model was developed for computing the effects of dryer design and operating conditions on dryer performance. The model describes a continuous flow fluidized bed dryer operating at steady state conditions. Calculated results from the model were found to be in good agreement with lignite drying data obtained from a pilot plant-scale dryer located at Great River Energy's Coal Creek Station.

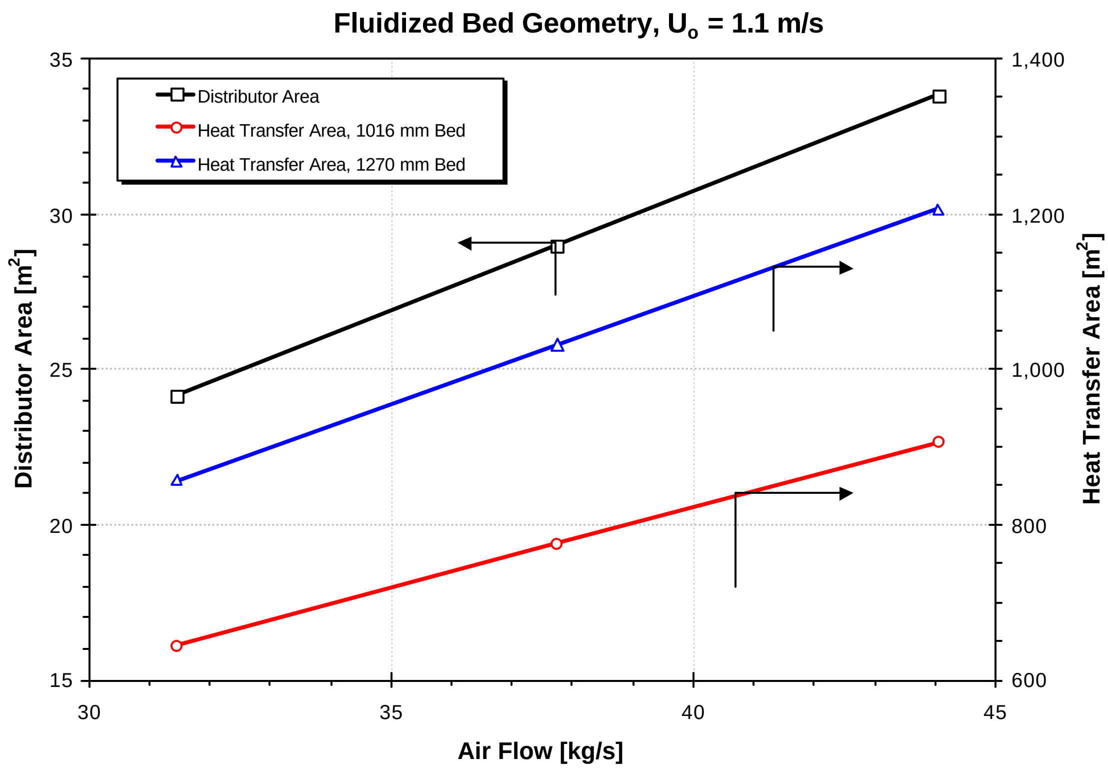


Figure 35: Effect of Air Flow Rate and Bed Depth on Distributor Area and Tube Bundle Surface Area

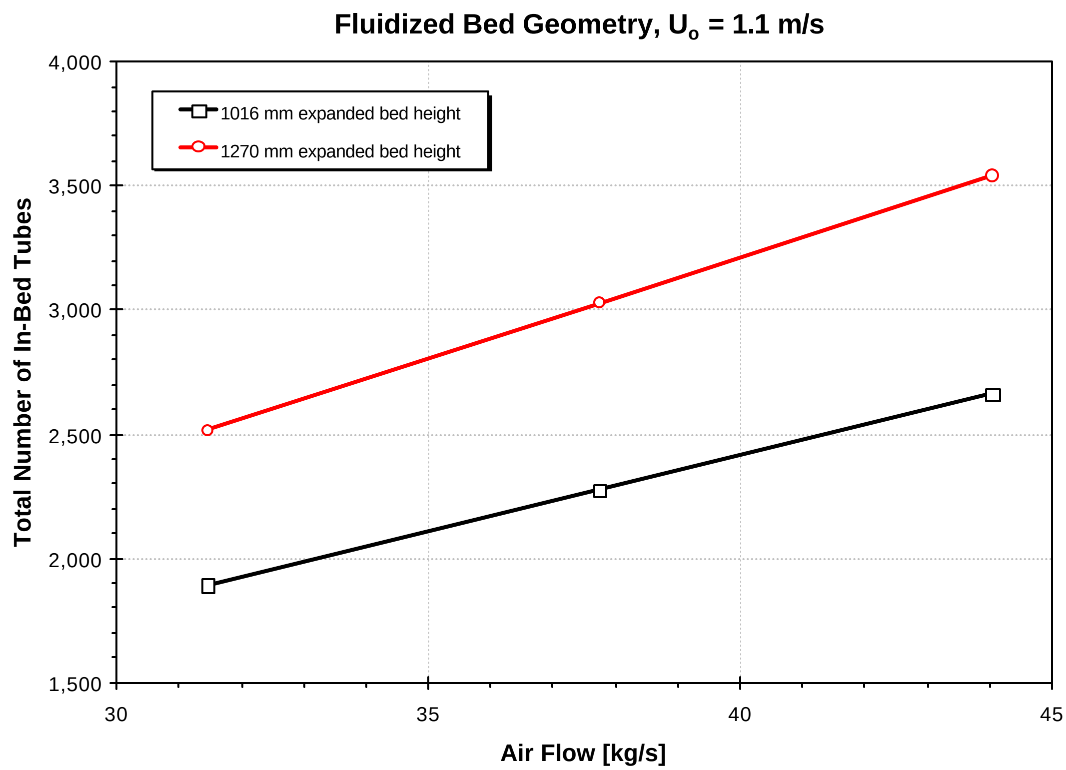


Figure 36: Effect of Air Flow Rate and Bed Depth on Number of In-Bed Tubes

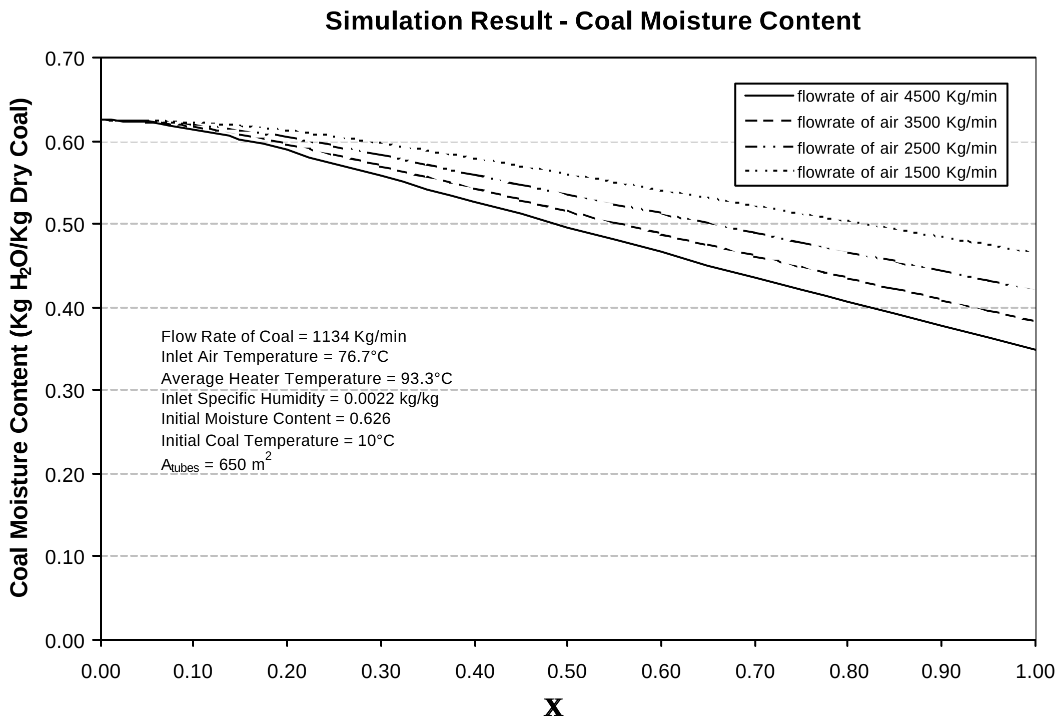


Figure 37: Variation of Coal Moisture with Distance From Inlet of Dryer and Air Flow Rate

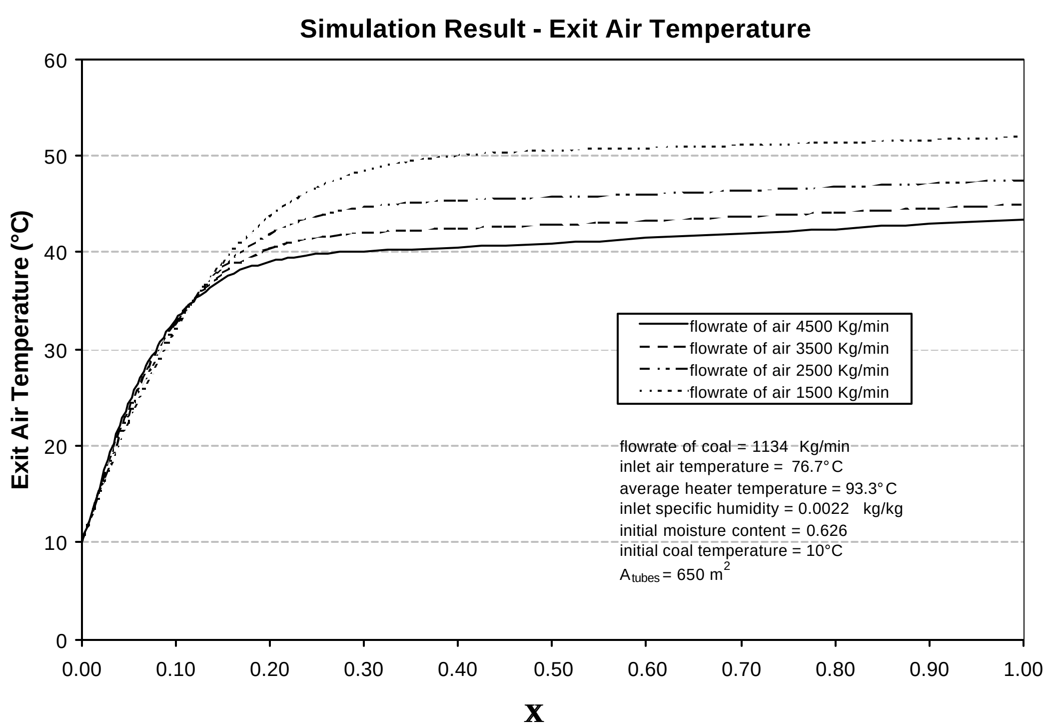


Figure 38: Variation of Exit Air and Bed Temperatures with Distance From Dryer Inlet and Air Flow Rate

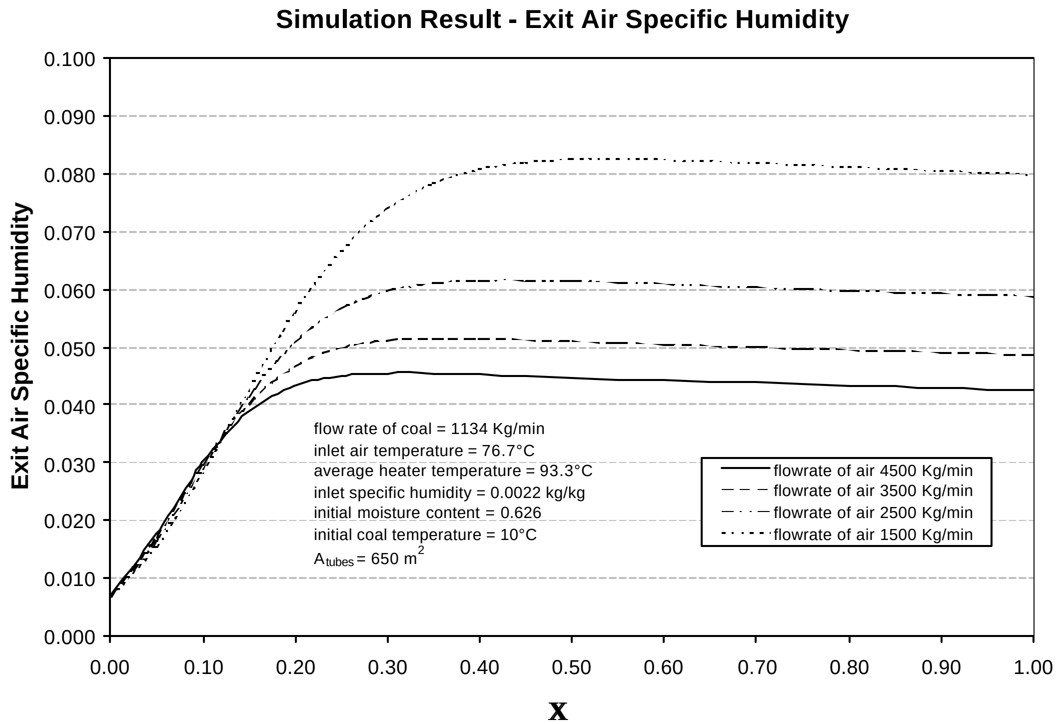


Figure 39: Variation of Exit Air Specific Humidity with Distance From Dryer Inlet and Air Flow Rate

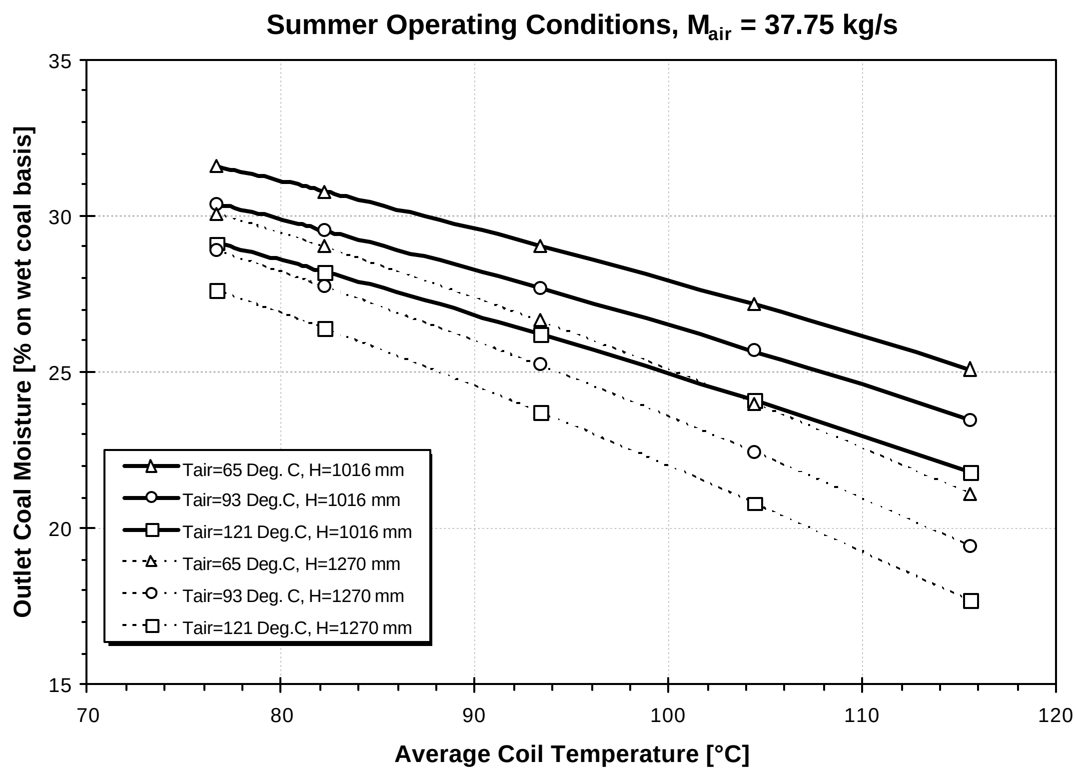


Figure 40: Effect of Tube Bundle and Fluidizing Air Temperatures on Outlet Coal Moisture

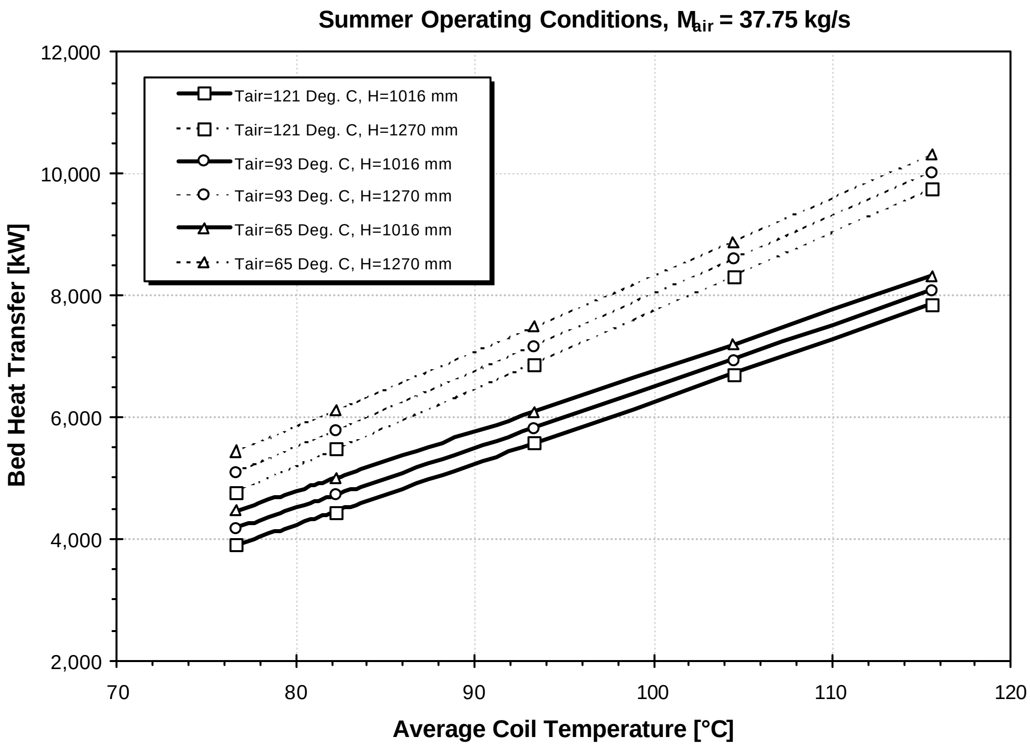


Figure 41: Effect of Tube Bundle and Fluidizing Air Temperatures and Bed Depth on In-Bed Heat Transfer

The first set of results was obtained from the Task 4 and 5 analyses to develop an optimized drying system design and determine the relative costs and performance impacts of drying lignite and PRB coals. The first order impacts of firing lignite and PRB coals, previously dried to various moisture levels, were calculated. Results are presented for coal, air and flue gas flow rates, fan and mill power, and net unit heat rate. Results were also generated on the effects of dryer design and operating conditions on the moisture of the coal leaving the dryer and the required in-bed heat transfer.

## REFERENCES


1. Bullinger, C., M. Ness, N. Sarunac, E. Levy, "Coal Drying Improves Performance and Reduces Emissions," Presented at the 27th International Technical Conference on Coal Utilization and Fuel Systems, Clearwater, Florida, March 4-7, 2002.

## NOMENCLATURE

| | |
|---|---|
| $d_p$ | Particle Size |
| $h_o$ | Settled Bed Depth |
| $\dot{m}_a$ | Air Flow Rate |
| $\dot{m}_{DC}$ | Mass Flow Rate of Dry Coal |
| $\dot{m}_{wet\ coal}$ | Mass Flow Rate of Wet Coal |
| $Q_{ave}$ | Average Heat Flux to Bed |
| $T_{a,\ in}$ | Air Inlet Temperature |
| $T_b$ | Bed Temperature |
| $U_o$ | Superficial Air Velocity |
| $x_i$ | Mass Fraction of Coal with Particle Size $d_{pi}$ |
| Y | Coal Moisture (Kg $H_2O$/Kg Moist Coal) |
| $\phi$ | Relative Humidity |
| $\Gamma$ | Coal Moisture $\left(\frac{\text{kg } H_2O}{\text{kg dry coal}}\right)$ |
| $\omega$ | Specific Humidity of Air |

## APPENDIX A
## DEFINITION OF COAL MOISTURE

It should be noted that two different definitions of coal moisture are used in this report. The moisture content of coal, Y, obtained as part of a Proximate coal analysis, is expressed on a wet coal basis, as Kg $H_2O$/Kg wet coal. The moisture contents in Figures 3, 4, 29 to 34 and 40 rely on this definition. For purposes of theoretical predictions of coal moisture and analysis of dryer test data, it is much more convenient to express the moisture on a dry coal basis, $\Gamma$, as Kg $H_2O$/Kg dry coal. Figures 7, 8, 12, 16, 20, 24 and 37 express coal moisture on a dry basis. The parameters Y and $\Gamma$ are related by the following equation.

$$Y = \frac{\Gamma}{1+\Gamma}$$

where $Y \equiv m_{H_2O} /(m_{H_2O} + m_{DC})$

$$\Gamma \equiv m_{H_2O} / m_{DC}$$

Figure A1 shows the relationship between Y and $\Gamma$.

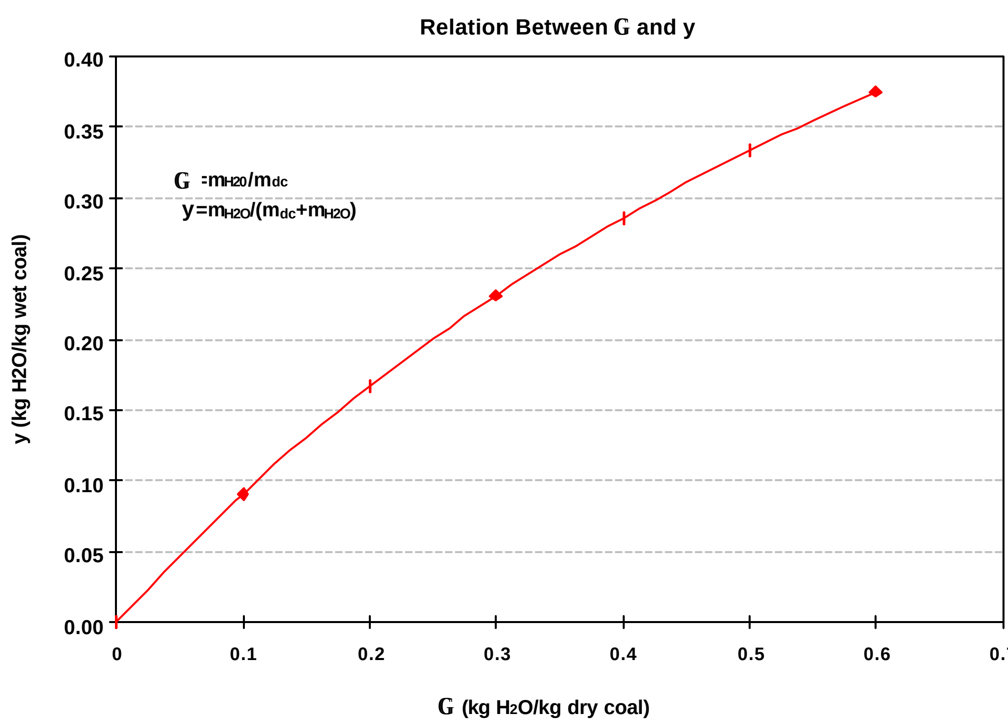


Figure A1: Relationship Between Two Different Definitions of Coal Moisture